A search for rapid photometric variability in symbiotic binaries

J. L. Sokoloski, Lars Bildsten and Wynn C. G. Ho

1Department of Physics and Astronomy, Southampton University, Highfield, Southampton SO17 1BJ
2Institute for Theoretical Physics and Department of Physics, Kohn Hall, University of California, Santa Barbara, CA 93106, USA
3Center for Radiophysics and Space Research, Department of Astronomy, Cornell University, Ithaca, NY 14853, USA

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ABSTRACT

We report on our survey for rapid (time-scale of minutes) photometric variability in symbiotic binaries. These binaries are becoming an increasingly important place to study accretion on to white dwarfs, since they are candidate Type Ia supernova progenitors. Unlike in most cataclysmic variables, the white dwarfs in symbiotics typically accrete from a wind, at rates greater than or equal to $10^{-9}$ M$_\odot$ yr$^{-1}$. In order to elucidate the differences between symbiotics and other white dwarf accretors, as well as to search for magnetism in symbiotic white dwarfs, we have studied 35 symbiotic binaries via differential optical photometry. Included in our sample are all but one of the symbiotics from the lists of Kenyon and Downes & Keyes with published $V$ magnitudes less than 14 and declinations greater than $-20^\circ$. Our study is the most comprehensive to date of rapid variability in symbiotic binaries. We have found one magnetic accretor, Z And, previously reported by Sokoloski & Bildsten. In four systems (EG And, BX Mon, CM Aql and BF Cyg), some evidence for flickering at a low level (roughly 10 mmag) is seen for the first time. These detections are, however, marginal. For 25 systems, we place tight upper limits on both aperiodic variability (flickering) and periodic variability, highlighting a major difference between symbiotics and cataclysmic variables. The remaining five of the objects included in our sample (the two recurrent novae RS Oph and T CrB, plus CH Cyg, o Ceti and MWC 560) had previous detections of optical flickering. We discuss our extensive observations of these previously known flickering systems in a separate paper. Five new variable stars were discovered serendipitously in the fields of the survey objects, and the observations of these stars are also presented elsewhere. We discuss the impact of our results on the ‘standard’ picture of wind-fed accretion, and speculate on the possibility that light from quasi-steady nuclear burning on the surface of the white dwarf hides the fluctuating emission from accretion.

Key words: accretion, accretion discs – methods: data analysis – surveys – binaries: symbiotic – stars: magnetic fields – stars: oscillations.

1 INTRODUCTION

Symbiotic stars, or symbiotic systems (SS), are wide binaries in which material is transferred from an evolved red giant star to either a white dwarf (WD), main-sequence star, or in a few cases, a neutron star (Kenyon 1986). The material can be transferred either as the red giant overflows its Roche lobe, or by Bondi–Hoyle capture of the red giant wind (see Yungelson et al. 1995 for modelling and population synthesis analysis of wind-fed SS). In most symbiotics, Bondi–Hoyle capture of the red giant wind by the WD is the mode of mass transfer (Luhhardt 1992; Iben & Tutukov 1996). Radiation from the hot component turns the red giant wind into a partially ionized nebula, producing the characteristic ‘symbiotic’ optical spectrum with high ionization state emission lines superimposed on the cool red giant continuum (Kenyon 1986).

Since most SS contain WDs (sometimes in a state similar to WDs at the centres of planetary nebulae; Kenyon & Webbink 1984; Mürset et al. 1991), it is important to place symbiotics within the context of other binaries with accreting WDs. Selected properties of several types of accreting-WD systems – cataclysmic variables (CVs), supersoft X-ray sources, and symbiotics – are listed in Table 1. It is clear that the three types of systems form a hierarchy of time-scales, sizes, and accretion rates. Our survey for rapid
variability in symbiotics represents part of an attempt to understand some of the phenomenological differences between symbiotics and the other WD accretors.

The mass-donor stars in CVs are low-mass main-sequence stars which overflow their Roche lobes. For CVs with orbital periods shorter than 2 h, the time-averaged accretion rate of $\sim 10^{-10} M_\odot\text{yr}^{-1}$ is set by gravitational radiation losses. For CVs with orbital periods in excess of 3 h, where magnetic winds are presumably driving angular momentum losses (Warner 1995), the time-averaged accretion rate is larger by nearly an order of magnitude. These CV-accretion rates are too low for thermally stable steady burning of the accreting fuel, and so this fuel is burned explosively in classical novae outbursts. In the classical supersoft X-ray sources, on the other hand, unstable mass transfer from an evolved main-sequence star with mass in excess of a solar mass experienced multiple events of much shorter duration that are most likely of thermonuclear origin (Mikołajewska & Kenyon 1992b). As mentioned above, the different accretion rates in CVs and supersoft sources cause the fuel on a CV WD to be burned unstably in a nova explosion, whereas the fuel in at least some supersoft sources appears to be burned quasi-steadily (van den Heuvel et al. 1992). The mass transfer rates in symbiotic systems bridge the gap between those in CVs and those in supersoft sources, and the thermal stability of the nuclear burning on the WDs in SS is still an open issue. The question of nuclear burning in classical symbiotics is important because the outbursts in these systems could be caused by processes related to the burning, and also because quasi-steady burning could allow the WD to increase in mass until it approaches the Chandrasekhar limit and explodes as a Type Ia supernova.

One way to address this issue, as well as the question of magnetism in the accreting WDs in SS, is to carry out rapid optical monitoring. The flickering$^1$ seen in CVs on short (e.g., minute) time-scales is presumed to come from material being accreted on to a WD (Bruch 1992; Bruch & Duschl 1993; Lyubarskii 1997; Yonehara, Mineshige & Welsh 1997; Fritz & Bruch 1998; Zamanov & Bruch 1998). The detailed origin of optical flickering in CVs is not well understood, although proposed mechanisms include unstable mass transfer from the mass-donor star leading to flickering on a disc hotspot, magnetic discharges in an accretion disc, turbulence in an accretion disc, and boundary layer instabilities leading to unsteady accretion (Bruch 1992).

Flickering-type optical variability has also been reported for some supersoft sources (Crampton et al. 1997; Meyer-Hofmeister et al. 1998; van Teeseling et al. 1998). Nuclear-burning time-scales and thermal time-scales associated with nuclear burning on a WD are generally thought to be too long for changes associated with this burning to produce rapid optical flickering. Thus the rapid variability in supersoft sources may instead be due to the reprocessing of nuclear-burning light (which is emitted predominantly in the soft X-ray regime) into the optical by a disc rim whose height, and therefore reprocessing area/volume, changes rapidly (Meyer-Hoffmeister et al. 1998). Nuclear burning on the surface of

\[1\] We refer to any stochastic or aperiodic brightness variations as ‘flickering’, even if the amplitude of these variations is small. CV-like stochastic variability of up to tenths of magnitudes is termed ‘large-amplitude’ or ‘strong’ flickering, whereas the smaller variations seen in the symbiotics discussed in Section 5.2 will be referred to as ‘small-amplitude’ or ‘weak’ flickering.
a WD is also a major source of luminosity in some SS. Reprocessed into the optical by the surrounding nebula, it could therefore significantly affect the optical variability properties of symbiotic systems.

Symbiotics are particularly interesting for the study of rapid variability, because some flicker and some do not. An early search for rapid variability in SS was conducted by Walker (1977), who observed 16 southern symbiotics from the South African Astronomical Observatory. Using 0.5- and 1-m telescopes, with typical observations lasting about 30 min, and with a time resolution of 1–5 s, he found that only the symbiotic recurrent nova (which by the nature of their thermonuclear outbursts are clearly not steadily burning fuel) had rapid variability with amplitude greater than his detection limit of 1–2 per cent. In 1996, a survey of eight northern hemisphere symbiotics was performed by Dobrzycka, Kenyon & Milone (1996). With observations up to almost 5 h in length, they detected rapid variability in one of the two recurrent novae they observed, RS Oph, and they also detected variability in two additional objects: MWC 560 and CH Cyg. They speculated about a possible inverse correlation between the hot component luminosity and presence of flickering. Our survey builds upon this previous work.

1.2 Periodic variability from magnetic accretion

In CVs with a sufficiently large WD magnetic field, the accretion flow is funnelled on to the WD polar caps, where the mostly radial accretion forms a stand-off accretion shock. The heated gas behind the shock produces X-ray emission, and through reprocessing at the stellar surface, optical light (Patterson 1994). The magnetospheric radius, \( r_{\text{mag}} \), is where the magnetic pressure of the WD dipolar field, \( B = B_i(R/r)^3 \) (where \( B_i \) is the magnetic field at the WD surface, and \( r \) is the distance from the centre of the star), is comparable to the ram pressure of the accreting matter. Setting these two pressures equal gives

\[
\frac{r_{\text{mag}}}{R} \approx 10 \left( \frac{R}{10^9 \text{ cm}} \right)^{5/7} \left( \frac{B_i}{10^9 \text{ G}} \right)^{4/7} \times \left( \frac{10^{-8} M_\odot \text{ yr}^{-1}}{M} \right)^{2/7} \left( \frac{0.6 M_\odot}{M} \right)^{1/7},
\]

(1)

where \( R \) is the WD radius, and \( M \) is the WD mass. Thus, if a WD has \( B_i \approx 10^5 \text{ G} \) (for \( M \approx 10^{-8} M_\odot \text{ yr}^{-1} \)), it will form a magnetosphere and, since the magnetic dipole is typically not aligned with the rotation axis, produce emission that is modulated on the WD spin period. Indeed, DQ-Her-like objects, which contain magnetized WDs accreting at rates roughly comparable to those in SS, pulsate in the optical at \( \sim 10–100 \text{ mmags} \) (Patterson 1994). The WD spin period, \( P_s \), is determined by the amount of angular momentum the WD has received from the accreting material or, in other words, how much it has been ‘spun up’. The shortest possible \( P_s \) for steady magnetic accretion is the Kepler period at the magnetosphere, \( P_{\text{eq}} = 2\pi r_{\text{mag}}^2/(GM)^{1/2} \), or

\[
P_{\text{eq}} = 12 \text{ min} \left( \frac{R}{10^9 \text{ cm}} \right)^{10/7} \left( \frac{B_i}{10^9 \text{ G}} \right)^{6/7} \times \left( \frac{10^{-8} M_\odot \text{ yr}^{-1}}{M} \right)^{3/7} \left( \frac{0.6 M_\odot}{M} \right)^{5/7}.
\]

(2)

A possible exception is T Pyx (Patterson et al. 1998).

If the WD is spinning faster than \( P_{\text{eq}} \), the disc material at the magnetospheric radius will be orbiting less rapidly than the magnetosphere is spinning, and thus will tend to slow the WD down rather than speed it up. With a minimal accretion torque \( N = M(GMR)^{1/2} \), the time for a WD in a symbiotic system to reach the equilibrium spin period, \( P_{\text{eq}} \), is

\[
t_{\text{spin-up}} = 2\pi I/N_{\text{eq}} = 4 \times 10^2 \text{ yr} \left( \frac{10^{-8} M_\odot \text{ yr}^{-1}}{M} \right),
\]

where \( I \) is the moment of inertia of the WD. This spin-up time is shorter than the red giant lifetime, so the WD can reach \( P_{\text{eq}} \) if it continually receives angular momentum at this rate. Also, from equation (2) we see that minutes to tens of minutes are the interesting time-scales for the search for magnetic WDs in SS. Note that these same time-scales are also the important ones to examine for some WD pulsations. The nuclei of planetary nebulae have been seen to pulsate with period of tens of minutes (Ciardullo & Bond 1996), and the first pulsating WD in a CV, with periods ranging from a few to tens of minutes, was recently found by van Zyl et al. (1999).

There are several motivations for a search for magnetic WDs in SS. First of all, theories of the origin of magnetism in WDs and theories of binary stellar evolution indicate that some SS should contain WDs with strong magnetic fields (Angel, Borra & Landstreet 1981; Sion et al. 1988; Yungelson et al. 1995). If magnetic WDs have evolved from the magnetic Ap and Bp stars, then the fraction of WDs in binaries such as symbiotics, CVs, and supersoft sources should be higher than the fraction that are magnetic in the field (which is about 2 per cent; Anselowitz et al. 1999). The different magnetic fractions should exist, because the WDs in interacting binaries come from progenitor populations that have, on average, higher masses. These progenitor populations will therefore contain a higher fraction of magnetic Ap and Bp stars than the progenitor population for field white dwarfs. In fact, 5–10 per cent of CVs contain WDs with magnetic fields \( B_i \approx 10^5 \text{ G} \) (Wickramasinghe & Ferrario 2000). This high magnetic fraction could, however, be due to selection effects, as some CVs are found by their optical or X-ray pulsations. Magnetic symbiotics have a different set of selection effects, and therefore provide an interesting testing ground for these theories.

Secondly, the flickering and other properties of several symbiotics (CH Cyg and MWC 560) have led Mikolajewski & Mikolajewska (1988), Mikolajewski et al. (1990a,b), Tomov et al. (1992), and Michalitsianos et al. (1993) to propose that these systems contain magnetic propellers. The detection of a magnetic WD in a SS by another means, such as discovery of a coherent oscillation, would allow a test of these propeller models if the new magnetic system were to experience a change in accretion rate.

Finally, the brightness oscillation associated with the spin of a magnetic, accreting WD in a symbiotic can be a useful diagnostic tool for these complex systems, as has already been seen in the case of Z And (Sokoloski & Bildsten 1999). Also, such systems provide an opportunity to study magnetically controlled accretion in an environment that is quite different from CVs.

1.3 Our search for rapid variability

The study of rapid variability from SS can help elucidate the relationship between SS and other accreting WD systems by providing direct information about the nature of the accretion region in SS, as well as the surrounding nebula. Building upon previous work by other authors (discussed in Section 1.1), we observed 35 northern symbiotics between 1997 January and 1999 July. Five of the survey objects are previously known flickerers (\( \theta \) Ceti = Mira AB, MWC 560, CH Cyg, and the recurrent novae T
CrB and RS Oph). In this paper we present our observations for 29 of the survey objects that have no previous detections of rapid variability. Seven of these 29 objects were included in the other searches for rapid variability mentioned above. Our observations of the well-known flickerers and the serendipitous discoveries, including a possible new short-period δ Scuti star, are discussed in separate papers (Sokoloski et al., in preparation). Our results for Z And, where we discovered the first stable, coherent oscillation ever seen in a symbiotic, are also presented in a separate paper (Sokoloski & Bildsten 1999). We describe our observations and the properties of the survey objects in Section 2, and the production of light curves in Section 3. The timing analysis and a discussion of sources of error are presented in Section 4. We display and discuss the results from both the non-flickering systems and the marginal flickering candidates in Section 5. Finally, in Section 6 we consider the implications of our results for the properties of the nebulae, accretion structures, and sources of power in symbiotic stars.

2 THE SURVEY

2.1 Observations

All of the observations presented here were performed using the 1-m Nickel telescope at UCO/Lick Observatory on Mt. Hamilton, near San Jose. In order to search for rapid variability, we used time-resolved differential CCD photometry. This procedure involved the repeated measurement of the programme star flux relative to an ensemble average of the fluxes of other stars in the field (the ‘comparison stars’). Each observation consisted of a series of exposures with either the unthinned, 2048 × 2048 Loral CCD (‘CCD 2’; 15-μm pixels), or on several occasions (fewer than 10 per cent of the total number of observations) the thinned, 1024 × 1024 SITE CCD (‘CCD 5’; 24-μm pixels). The field of view for CCD 2 is 6.3 × 6.3 arcmin2, and the field of view for CCD 5 is 5.0 × 5.0 arcmin2. Exposure times ranged from 4 to 100 s, with a dead time between exposures of roughly 15 to 28 s for chip read-out and pre-processing, depending upon the number of rows read out. A Johnson B filter was used for most observations. This filter was selected to reduce the amount of light detected from the red giant, while still allowing for a large enough detected flux to produce high signal-to-noise ratio (S/N) measurements in about 1 min. For several extremely bright objects, a liquid CuSO4 (+ 1 mm UG2) U-band filter was used, and if multiple observations were done for a single object, a U-band observation was sometimes included. Table 2 is the complete log of the observations described in this paper. A typical observation lasted 3–4 h, and so 1–3 observations were performed per night.

The exposure times were chosen to maximize the resulting S/N, while not saturating the programme star or any comparison stars, and while keeping the time between individual exposures to less than 2 min. Longer integrations would have reduced our sensitivity to oscillations with periods in the interesting range of a few to tens of minutes, and to the most rapid flickering. We also generally avoided exposures of just a few seconds, since for short exposures the comparatively long read-out time would have made the duty cycle low, and the observations rather inefficient.

In order to obtain evenly spaced exposures and thus produce data sets compatible with standard fast Fourier transform (FFT) routines, we usually employed a timing system developed especially for this project by Will Deitch. Therefore, for most of the observations, the time between exposure starts was constant to very high precision. This timing system was not available when our earliest observations were done. For some of these early observations, the time between exposures varied by 1–2 s, or about 5–10 per cent.³

2.2 Differential CCD photometry

Differential CCD photometry can yield useful data even when the weather conditions are not ideal. Assuming that the point spread function (PSF) is the same for each star on the chip, and that clouds reduce the count rate for each object by the same fraction, the ratio of fluxes extracted from the same aperture for constant-brightness stars should remain constant despite variable clouds and/or seeing changes. Two examples of the usefulness and capabilities of differential photometry are shown in Figs 1 and 2. Fig. 1 shows raw light curves for the symbiotic V443 Her, another star in the same field of view, and the differential light curve. Even though each of the raw light curves has dips due to clouds or changes in seeing, the differential light curve is flat to within the error bars. Using differential photometry, we can thus place an upper limit on the intrinsic variability of V443 Her. In Fig. 2, raw light curves for the symbiotic star T CrB and another star in its field are shown, as well as the differential light curve. Again, the raw light curves show variability due to clouds, seeing changes, and variable airmass. However, this time the ratio shows that T CrB is in fact intrinsically variable.

2.3 Sensitivity to an oscillatory signal

Before describing our techniques in more detail, we give an estimate of our sensitivity. A typical symbiotic star has $B \approx 12$. The photon count rate for an object of magnitude $m$ is given by

$$N_c = N_0 \times 10^{-m/2.5} \times \text{area} \times \text{bandwidth} \times QE,$$

where $N_0 = 1400 \text{cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$ (the flux density for a $B = 0$ object), ‘area’ is the mirror collecting area, ‘bandwidth’ is the effective bandwidth obtained by integrating over the transmission of the filter and the atmosphere, and $QE$ is the quantum efficiency of the CCD. Plugging in an area of 7850 cm² (not taking into account the secondary mirror blockage), an effective bandwidth of 380 Å (for an airmass of 1.5 and using extinction tables from Hayes & Latham 1975), and a quantum efficiency of 0.15 (rough estimate for Lick’s CCD 2), we find $N_c \approx 9900 \text{photon s}^{-1}$ for $B = 12$. If uncertainties are set purely by photon counting statistics of the source (e.g., if all comparison stars are much brighter than the programme star, the background is low, and systematic uncertainties are negligible), then the S/N for detection of a pulsed signal is given by

$$\frac{\text{Signal}}{\text{Noise}} = \frac{(1/4)p N_c t}{\sqrt{N_c t}},$$

where $p$ is the pulse fraction, and $t$ is the total integration time. The

³ The early version of our timing system introduced some timing error that affected our sensitivity to periodic oscillations. Since we arrived at our pulse amplitude upper limits by repeatedly injecting oscillations into our real data using the same sampling as the real light curve, however, the upper limits derived in this way remain valid. Comparisons between simulations with even sampling and slightly uneven sampling, as we had in our early data, indicate that the sensitivity to periodic oscillations is reduced by a few per cent.
factor of 1/4 in the numerator of equation (4) comes from the fact that we want to divide the signal counts into at least four phase bins. If we demand an S/N of 5 in each phase bin, and we assume 3 h of total integration time, then our observations are sensitive to bins. If we demand an S/N of 5 (in each phase bin), and we assume $B_0$; this rough estimate is comparable to the result of the second is for the power spectrum.

In order to detect mmag-level variability, we required roughly $10^5$ stellar counts per integration. Since we wanted to probe minute-

differential photometry timing analysis from Lick Observatory. Table 3 lists the binaries included in our survey. They were taken generally be achieved for stars brighter than cosmic rays, extremely poor weather, or other problems. If two values are given, the first is for the light curve, and the second is for the power spectrum.

The times between data points are only approximate on 1997 March 13 due to a clock problem.

## 2.4 Source selection

Table 3 lists the binaries included in our survey. They were taken from the lists of Kenyon (1986) and Downes & Keyes (1988), and were selected primarily because of their observational suitability for differential photometry timing analysis from Lick Observatory. In order to detect mmag-level variability, we required roughly $10^5$ stellar counts per integration. Since we wanted to probe minute-long time-scales, the programme star had to provide at least $\approx 800$ count s$^{-1}$ within the extraction region. This count rate could generally be achieved for stars brighter than $B = 14$ mag with CCD 2, and for slightly fainter objects with CCD 5 (if the comparison stars were significantly brighter and therefore did not add much uncertainty). Note, however, that if there are only a few faint

\begin{align}
 p &= 0.002 \left( \frac{N_c}{900 \text{ s}^{-1}} \right)^{-1/2} \left( \frac{t}{3\text{ h}} \right)^{-1/2},
\end{align}

for a $B = 12$ star. This rough estimate is comparable to the result of the more careful calculation given in equation (26). In practice, we cannot quite reach this level, as explained in the detailed discussion in Section 3.
comparison stars (fainter than the programme star at $B$), then these stars and not the programme star set the variability-amplitude detection limit. Since typical values of $B - V$ for symbiotics lie between 0 and 1 (see Table 3), and $V$ magnitudes were more readily available, in practice we selected objects with published $V$ magnitudes less than 14.

For the survey, slow novae still in outburst were generally avoided, since the expanded envelopes in these systems would hide any rapidly variable processes near the surface of the WD. However, a few slow-novae-like systems and slow novae well after decline from maximum were observed (PU Vul, AG Peg and AS 296). Finally, since Lick Observatory is at 37° latitude, we could produce reasonable light curves only for symbiotics with $d_{B*}^2 < 25°$. In the end, we observed all of the objects from Kenyon (1986) and Downes & Keyes (1988) that were not slow novae, and that have $V < 14$ mag and $\delta > -20$, except one. In addition, we observed two objects that were slightly more southern (RW Hya and BD $-21°3873$), one slightly fainter object (CM Aql), the symbiotic-like systems Mira AB ($\alpha$ Ceti) and MWC 560, and the neutron-star symbiotic HD 154791, for a total of 35 objects. Most

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**Figure 1.** Example of the capabilities of differential photometry. In the top panel, the raw light curve for V443 Her from 1997 April 7 (UT) is shown. The raw light curve for a second star in the field is shown in the middle panel. In both cases, dips due to clouds or other atmospheric changes are evident. In the bottom panel, the differential light curve formed from the ratio of V443 Her and an ensemble average of four comparison stars is shown. The atmospheric variability is completely removed.

**Figure 2.** A second example of the capabilities of differential photometry. For this observation of T CrB, we were able to remove the atmospheric effects and see the variability intrinsic to the source. The differential light curve was created with an ensemble average of four comparison stars.

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### Table 3. Properties of the symbiotics surveyed.

| Name    | RA(2000) (h m s) | Dec(2000) (° ′ ″) | IR Type | Outburst Typea | IR Componentb | $P_{\text{orb}}$ (d) | $D_{\odot}$ (kpc) | $V^c$ (mag) | $B^c$ (mag) | Refs.  |
|---------|------------------|-------------------|---------|----------------|---------------|-----------------|-----------------|-------------|-------------|--------|
| EG And  | 00 44 37.2       | +40 40 46         | S       | C              | MS            | 482.6           | 0.30–0.35       | 7.5, 7.2    | 8.8         | 13, 4, 5, 8 |
| AX Per  | 01 36 16.9       | +54 15 35         | S       | C              | WD            | 680.8           | 2–3             | 12          | 10.8        | 12, 3, 4, 5, 8 |
| V471 Per| 01 58 49.7       | +52 53 48         | D†      |               |               | 132, 13.1       | 14.1            | 1.5         |             | 1.5 |
| Mira    | 02 19 20.7       | −02 58 28         | S       |                | WD            | 3.0             | 4.5             | 2.5         |             | 2.5 |
| S 32    | 04 37 45.3       | −01 19 09         | S       |                |               | 13.5            |                 | 6           |             | 6 |
| UV Aur  | 05 21 49.0       | +32 30 44         | S       |                |               | 79.96           | 11.0            | 1.5         |             | 1.5 |
| BX Mon  | 07 25 23.9       | −03 35 59         | S       | WD             | 100–1000       | 1401            | 12.9           | 9.5         | 12, 3, 5     | 12, 3, 5 |
| MWC 560 | 07 25 51.2       | −07 44 04         | S       | WD             | 100–1000       | 1930            | 9.7            | 10.0        | 2.5, 8      | 2.5, 8 |
| TX CVn  | 12 44 42.2       | +36 45 49         | S       | C              | WD            | 199             | 93.9           | 10.4        | 1.5, 8      | 1.5, 8 |
| RW Hya  | 13 34 18.2       | −25 22 49         | S       | WD             | 350            | 370.2           | 0.6–1.3        | 10.8, 9      | 10.2, 12, 3, 4, 5, 8 |
| BD−21°3873 | 14 16 34.3    | −21 45 51         | S       |                |               | 281.6           |                 | 10.2        |             | 1.5, 8 |
| T CrB   | 15 59 30.2       | +25 55 12         | S       | RN             | 5–40           | 227.57          | 100, 10.2      | 11.5        | 12, 3, 5     | 12, 3, 5 |
| Hen 1341| 17 08 36.7       | −17 26 29         | S       | RD              |               | 2.4             | 12.0           | 1, 3, 4, 5    |             | 1, 3, 4, 5 |
| RS Oph  | 17 50 13.2       | −06 42 27         | S       | RN             | WD             | 455.7           | 0.6            | 11.5        | 12, 3, 5     | 12, 3, 5 |
| AS 289  | 18 12 22.2       | −11 40 07         | S       |                | WD             | −100            |                 | 1, 3, 5, 8    |             | 1, 3, 5, 8 |
| YY Her  | 18 14 34.1       | +20 59 18         | S       | C              | WD             | 590             | 3.8–5.1        | 12           | 11.7        | 1.5, 8 |
| AS 296  | 18 15 06.4       | −00 18 59         | S       | SN             |               | 1.8             | 10.5           | 13.5        | 14.5        | 14.5 |
| S 149   | 18 18 56.2       | +27 26 10         | S       |                |               | 13.5            |                 | 6           |             | 6 |
| V443 Her| 18 22 07.7       | +23 27 20         | S       | WD             | −1000          | 594             | 1.9–2.7        | 11.5, 12.4    | 12, 3, 4, 5, 8 |
| FN Sgr  | 18 53 54.4       | −18 59 42         | S       | C              | WD             | 567.2           | 5.0            | 9.0         | 14.5, 8     | 14.5 |
| CM Aql  | 19 03 35.1       | −03 03 14         | S       |                |               | 18              | 15             | 13          | 15.8        | 15.8 |
| V919 Sgr| 19 03 45.1       | −16 59 54         | S       |                | WD             | 2.1             | 12.5, 11.8     | 12.5, 14.5   |             | 14.5 |
| BF Cyg  | 19 23 53.4       | +29 40 28         | S       | C              | WD             | 3000, 5000      | 756.8          | 2.6–5.0      | 12.1, 10.3   | 10.2, 12, 3, 4, 5, 8 |
| CH Cyg  | 19 24 33.1       | +50 14 29         | S       | WD             | 1–10           | 5700            | 0.22–0.4       | 7.8, 10.2    | 12, 3, 4, 5, 8 |
| AS 360  | 19 45 49.3       | +18 36 45         | S       |               |               | 10.0            | 11.0           | 11.0        | 14.5        | 14.5 |
| CI Cyg  | 19 50 12.2       | +35 41 03         | S       | C              | WD             | 3000–5000, 560  | 855.3          | 12.1–2.1     | 11.1        | 12, 3, 4, 5, 8 |
| PU Vul  | 20 21 13.3       | +21 34 18         | S       | SN             | WD             | −1000          | 4900           | 6.0          | 9.8, 11.7   | 12, 3, 4, 5, 8 |
| He2-467 | 20 35 57.3       | +20 11 33         | S       |                |               | 13              |                 | 1           |             | 1 |
| S 180   | 20 39 20.6       | −05 16 58         | S       |                |               | 13.5            |                 | 5.6         |             | 5.6 |
| S 190   | 21 41 45.0       | +02 43 53         | S       |                |               | 103.10.5        | 11.1           | 11.1        |             | 11.1 |
| AG Peg  | 21 51 02.2       | +12 37 31         | S       | SN             | WD             | −1000          | 816.5          | 0.6–0.72     | 9.4, 8.7     | 9.8, 12, 3, 4, 5, 8 |
| Z And   | 23 33 40.0       | +48 49 06         | S       | C              | WD             | 500–2000        | 758.6          | 0.98–1.6     | 10.5        | 11.9        | 12, 3, 5, 8 |
| R Aqr   | 23 43 49.5       | −15 17 02         | S/D†    | WD             | 1–100          | 16000          | 58.7           | 8.8         | 12, 3, 5, 8 |

aC= classical symbiotic outburst = Z And-type outburst; RN = recurrent nova; SN = symbiotic nova = symbiotic slow nova.
bObjects listed as ‘hot stellar sources’ (HSS) by Dobrzycka et al. (1996) are listed here as WDs. HD 154791 is the one neutron star system.

If more than one value is given, the different values are from different authors. Note that symbiotics are variable, so the $V$ magnitudes given may not reflect current source brightnesses. These magnitudes are, however, typical values for most objects.

Refers therein for all.
of the symbiotics we observed presumably contain WD accretors (Mørst et al. 1991), although the two strongest candidate main-sequence systems (CI Cyg and AX Per; see Kenyon et al. 1991 and Mikolajew ska & Kenyon 1992a, and references therein) are also included in our sample. All of the symbiotics in the sample are IR S-types, except for one D-type system (V471 Per). Some properties of the survey objects are listed in Table 3. The previously known flickerers and Z And are included for comparison, even though we present our observations of these systems elsewhere.

3 DATA REDUCTION

A typical observation, or series of exposures, produced between 50 and 250 images, and the complete survey consisted of over 80 such observations. Roughly half of these observations were of the previously known flickering systems, and the other half are presented here. The data reduction and analysis was done in IDL, and it included the use of software based upon standard IRAF routines. For each observation, the data were reduced using the standard techniques (e.g. Gilliland 1992).

3.1 Estimation of uncertainties

Before describing the aperture photometry and generation of light curves, we discuss our method for estimating the uncertainties in the CCD photometry. An understanding of the uncertainties is crucial for identification of low-level variability intrinsic to the source, especially low-level flickering-type variability. We found the formal uncertainties for each star in each image from the source, especially low-level flickering-type variability. We found crucial for identification of low-level variability intrinsic to the
c-\text{counts in electrons (or photons), } n_{\text{bins}} \text{ is the number of integrated stellar source counts in electrons (or photons), } n_{\text{sky}} \text{ is the area of the software aperture in bins, } n_{\text{sky}} \text{ is the area of the region used for background estimation in bins, } N_{\text{sky}} \text{ is the sky (background) counts (electrons/bin), } N_{\text{sky}} = \text{the read noise (in rms electrons/bin), } N_{\text{D}} \text{ is the dark current (electrons/bin). We refer to bins instead of pixels, because we always used CCD 2 with } 4 \times 4 \text{ pixel binning and CCD 5 with } 2 \times 2 \text{ pixel binning. Not included in equation (6) is digitization error, which is less than the value of the gain (typically } 6.8 \text{ e}^{-}/\text{ADU and } 7.7 \text{ e}^{-}/\text{ADU for our two CCDs}), \text{ and therefore always negligible for us.}

For our observations, } N_{\text{S}} \text{ generally ranged from } 50 \text{ to } 500, \text{ read noise squared had the values } N_{\text{D}}^2 = (100 \text{ to } 150), \text{ and the dark current was } N_{\text{D}} < 1(t_{\text{int}}/100 \text{s}). \text{ Therefore we can drop the dark-current term and rewrite the uncertainty as}

\[\sigma_{\text{CCD}}^2 = c + n_{\text{bins}}(N_{\text{S}} + N_{\text{sky}}^2) + n_{\text{bins}}(N_{\text{S}} + N_{\text{sky}}^2).\] (7)

The number of stellar counts, } c, \text{ was typically a few times } 10^6 \text{ to } 10^8. \text{ The second term, } n_{\text{bins}}(N_{\text{S}} + N_{\text{sky}}^2), \text{ which arises from Poisson
fluctuations of the background and readnoise within the aperture, was approximately } 10^5 \text{ for low-background periods, but could approach } 10^7 \text{ when a bright Moon and clouds were present. The average background count rate for an observation was primarily a function of the phase of the moon, whether or not there were low clouds blocking the light from San Jose, and the cloud-cover overhead. The third term arises from the Poisson uncertainty in the estimation of the background level, and was a factor of } n_{\text{sky}}/n_{\text{sky}}^2 = 0.1 \text{ smaller than the second term. In the data analysis, the formal uncertainties were calculated by replacing the expression } N_{\text{S}} + N_{\text{sky}}^2 \text{ in equation (7) with the measured variance from the sky annulus. This was a conservative approximation, as the measured variance should be greater than or equal to } N_{\text{S}} + N_{\text{sky}}^2.

In addition to Poisson uncertainties, there was also an inescapable contribution to source variability from atmospheric scintillation. Scintillation refers to the brightness variations of a star viewed through a finite aperture pupil due to temperature-related fluctuations in the refractive index of the atmosphere. As the spatial refractive-index fluctuations in the turbulent atmosphere move between the telescope and the star at the wind speed, the wavefront is perturbed, and the amount of starlight received by the telescope will vary. According to Young’s formulation (Young 1967) of Reiger’s theory of scintillation (Reiger 1963),

\[s_{\text{scint}} = \frac{c_{\text{rms}}}{c} = S_0d^{-2/3}X^{1/2}e^{-h/b_0}d^{-1/2}.\] (8)

where } s_{\text{scint}} \text{ is the fractional rms variation due to scintillation, } c_{\text{rms}} \text{ is the rms variation in the source counts, } c \text{ is the mean value of the number of source counts, } c, \text{ from a series of measurements, } S_0 \text{ is a constant that Young determined empirically to be } 0.09, \text{ } d \text{ is the mirror diameter in cm, } X \text{ is the airmass, } h \text{ is the observatory altitude in metres, } b_0 = 8000 \text{ m, and } D \text{ is the frequency bandpass of time-series sampling rate in Hz (i.e., } f = 1.0t_{\text{int}}, \text{ where } t_{\text{int}} \text{ is the integration time for each exposure in seconds). The expression for the total formal photometric error for each star in a field is thus}

\[\sigma_{m}^2 = \sigma_{\text{CCD,m}}^2 + s_{\text{scint}}^2 N_{\text{S}}c_{\text{rms}}^2.\] (9)

where } \sigma_{\text{CCD,m}} \text{ is } \sigma_{\text{CCD}} \text{ from equation (6) for star } m \text{ with } c_{\text{m}} \text{ source counts.}

For the Nickel telescope at Lick Observatory, where } d = 100 \text{ cm and } h = 1280 \text{ m, we obtain the following}

\[s_{\text{scint}} = 0.84 \text{ mmag } \frac{S_0}{0.09} \left(\frac{d}{100 \text{ cm}}\right)^{-2/3} \left(\frac{X}{1.5}\right)^{1/2} e^{-h/b_0}d^{-1/2}.\] (10)

Assuming that } S_0 = 0.09 \text{ is applicable to our observations (this is a conservative assumption, since whereas Young 1967 measured this value for McDonald Observatory, Gilliland & Brown 1992 inferred

\[\sigma_{\text{CCD,m}} = \sigma_{\text{CCD}} - \sqrt{\frac{\text{counts}}{100 \text{ cm}}} - \sqrt{\frac{\text{h}}{1280 \text{ m}}}.\] (11)

5 We will often express fractional rms variation in units of mmag. For a change in flux } \Delta F \text{ that is small compared to the average flux } F, \text{ we have } \Delta m = 2.5 \log (F + \Delta F/F) = (2.5/\ln 10) \log (1 + \Delta F/F) = 1.086(\Delta F/F), \text{ where } \Delta m \text{ is the magnitude change corresponding to } \Delta F. \text{ Therefore a } 0.1 \text{ per cent flux variation is approximately equal to a magnitude change of } 1 \text{ mmag.}

6 The frequency bandpass scaling of } s_{\text{scint}} \text{ arises from the fact that the power spectrum of scintillation is flat (Reiger 1963; Young 1967), up to a high-frequency cut-off. Since the variance is proportional to the integral of the power, } s^2 = \int_{f_1}^{f_2} P(f) df = \frac{f_2 - f_1}{f_1} = \text{the Nyquist frequency and } f_1 = 0, \text{ and the rms deviation } s_{\text{scint}} \text{ is proportional to } t_{\text{int}}^{1/2} \Delta F^{1/2}.\]
a value of 0.07 for Kitt Peak National Observatory and speculated
that even this value might be an upper limit), we then find that even
for the lowest airmass of 1.0, we still have a 0.5-mmag contribution
to the rms variation from scintillation for \( t_{\text{int}} = 60 \) s. The
contribution climbs to 1.8 mmag for \( X = 2.5 \) and \( t_{\text{int}} = 60 \) s,
which is comparable to the standard deviation from Poisson
statistics for our typical count rates. Fig. 3 shows the rms variation
due to scintillation for several typical observations. Note that
variability due to scintillation is independent of the software
extraction aperture size.

3.2 Aperture photometry and construction of light curves

For the programme star and as many comparison stars as possible
(usually 2 to 6), the counts were extracted from circular apertures
with radii that typically ranged from 4.0 to 8.0 bins for CCD 2 and
5.0 to 9.5 bins for CCD 5 (3 to 6 arcsec in both cases). The
background was estimated from an annulus surrounding the star of
interest. Very faint comparison stars were not used, because for
faint objects, the increased number of data points that became
unusable due to cosmic ray contamination outweighed the small
improvement in the S/N of the final light curve. Stars with blended
images were also not used as comparisons. We elected to use
simple aperture photometry instead of PSF fitting for two reasons.
First, most of our fields did not contain many stars, and the PSFs
for these stars were not well sampled due to our coarse binning.
Second, the PSFs changed significantly as a function of time, so
that a reliable PSF would have been difficult to obtain.

For each image in a sequence of \( N \) images used to produce a light
curve, the ratio of the programme star counts to a weighted sum
of comparison star counts was found:

\[
x(i) = \frac{A}{\sum_{m=1}^{K} w_m c_m(i)} c_p(i), \quad i = 0, \ldots, N - 1
\]

(11)

where \( x(i) \) is the count ratio for the \( i \)th image, \( c_p(i) \) is the
background subtracted source counts for the programme star in the
\( i \)th image, \( c_m(i) \) is the background-subtracted source counts for
the \( m \)th comparison star in the \( i \)th image, \( w_m \) is the weight for the
\( m \)th comparison star (same for every image, \( i \)), \( K \) is the number
of comparison stars used, and \( A \) is a normalization factor,

\[
A^{-1} = \frac{1}{N} \sum_{j=0}^{N-1} \frac{c_p(j)}{\sum_{m=1}^{K} w_m c_m(j)}.
\]

The weights are given by

\[
w_m = \frac{c_m}{\sigma_m} = \frac{1}{\sum_{j=0}^{N-1} \frac{c_m(j)}{\sigma_m^2(j)}},
\]

(13)

where \( \sigma_m \) is the formal uncertainty on \( c_m \), the source counts for star
\( m \), from equation (9), and \( c_m \) and \( \sigma_m^2 \) are the averages of \( c_m \) and \( \sigma_m^2 \)
over all \( N \) images. This form of the weights can be derived by
minimizing the uncertainty in the count ratio \( x(i) \) (given in
equation 14). Note that the weights go to 1 in the Poisson limit of
\( \sigma_m^2 = c_m \). This weighting scheme is the same as that used by
Gilliland & Brown (1988), except that no position or colour
information is included. The series of \( x \) values has been normalized
to unity, so a variation of 0.001 in \( x \) corresponds closely to 1 mmag.
We refer to the series of \( x \) values as the light curve, and individual \( x \)
values as data points. The formal uncertainty for each data point
can be expressed as a function of the uncertainties for the

\[
s_x^2 = \frac{\sum_{j=0}^{N-1} \left[ \frac{1}{\sigma_p^2(j)} \right] \left[ \frac{1}{\sigma_m^2(j)} \right]}{\sum_{j=0}^{N-1} \left[ \frac{1}{\sigma_p^2(j)} \right]}. 
\]

(15)

The variance is approximately equal to the fractional variance in
the expression above because, for the data presented here, the \( x(i) \)
are all very close to unity.

In constructing the final light curve, the aperture selected was
generally the one that maximized the S/N, or in other words,
momimized the expected variance \( s_x^2 \), where \( s_x^2 \) is a weighted
average of the \( \sigma_x^2 \) over all the points in a light curve,

\[
On the few occasions when the aperture which produced the best
formal S/N was very small (radius less than about 4 bins, or
3 arcsec for CCD 2), a slightly larger aperture was actually used to
avoid problems with pixelization noise or other systematic
uncertainties if these systematic errors were seen to be present in
the comparison stars at small extraction radii. Pixelization noise
was only a problem for small apertures (see Section 4.3). A single
aperture was used in extracting counts for the programme and all
comparison stars throughout an entire light curve. The use of
different apertures for different parts of the light curve would
improve the formal S/N, as the background generally changed
throughout an observation. However, we chose not to do this, as
it would introduce a new source of error because the PSFs are not
quite the same for the different stars in the field. For observations
with a low background count rate, using a larger aperture increased
the source counts extracted without significantly increasing counts
from the background, and therefore improved the S/N. For
observations with a high background rate, on the other hand,
smaller apertures reduced the uncertainty introduced by the
background light and therefore produced higher S/N light curves.
A few typical plots of \( s_{\text{exp}} \) as a function of aperture, as well as the measured rms variation, are shown in Fig. 4.

Data points contaminated by radiation events (‘cosmic rays’) were omitted, as were points with extremely high background, or taken during exceptionally poor weather conditions. Data points contaminated by cosmic rays were identified in two ways. First, the residuals from Gaussian fitting were compared for the various stars in a field. This method worked well for cosmic rays in the wings of a PSF, but less well for cosmic rays that hit near the centre of the PSF. Next, light curves were formed for all possible pairs of comparison stars in a field. If any point in these light curves was suspiciously high or low (by greater than at least 5\( \sigma \)), that point was not used in the creation of the final ensemble average. Occasionally, individual extreme high points were due to a cosmic ray hit near the programme star itself, and these points were also removed. We were much more conservative, however, about removing points in which the programme star was the one thought to be contaminated. In general, only about 5 to 10 points per light curve were rejected because of cosmic ray contamination. This number is consistent with the expected rate of cosmic ray hits, given the measured distribution of cosmic rays from dark images. We measured the rate of cosmic ray hits to be 1.25 \( \times \) 10\(^{-6} \) s\(^{-1} \) bin\(^{-1} \) for CCD 2. The number of contaminated data points per observation, \( n_{\text{crs}} \), is then expected to be

\[
n_{\text{crs}} \approx 5 \left( \frac{K + 1}{5} \right) \left( \frac{N}{120} \right)^{6} \left( \frac{t_{\text{rat}}}{60 \text{s}} \right),
\]

where \( K \) is the number of comparison stars, \( N \) is the number of data points, \( b \) is the extraction radius in bins, and \( t_{\text{rat}} \) is the integration time (note that radiation events can also occur during read-out). The distribution of total counts in a cosmic ray event, measured from two 30-min dark images, is plotted in Fig. 5. The most typical event size was approximately 200 ADU \( \approx 1400 \) e\(^{-} \). Since a typical number of source counts was on the order of \( 10^5 \), an unidentified cosmic ray within the stellar aperture could therefore artificially increase the source flux by roughly 1 per cent.

Finally, the resulting light curve was fitted with a second- or third-order polynomial, depending upon the length of the observation, to remove any slow variations due to changing airmass. These variations could exist, despite using differential photometry, when the programme star and comparison stars had significantly different colours.

### 4 TIMING ANALYSIS

The survey light curves were analysed in several ways. First, the measured rms variation was compared to that expected from the CCD equation and scintillation. Next, power spectra were computed to search for periodic signals, and Monte Carlo simulations performed to determine our detection limits for sinusoidal variations in each light curve.

#### 4.1 Aperiodic variability

The crux of our search for aperiodic variability, or flickering, was comparing the measured rms variation for each light curve (denoted \( s \)) to the rms variation expected from the known errors, denoted \( s_{\text{exp}} \), defined in equation (15). The measured rms variation is obtained from the data using the general expression for the variance when the errors on each data point are different

\[
\chi^2 = \frac{N - 1}{\sum_{j=0}^{N-1} \left( \frac{x_j - \bar{x}}{\sigma_j} \right)^2}
\]

Note that comparing the two quantities \( s \) and \( s_{\text{exp}} \) is actually the same as calculating \( \chi^2 \) for the hypothesis of a constant flux (Bevington 1969, p. 188). If \( s \) and \( s_{\text{exp}} \) are comparable (i.e., \( s/\sigma_{\text{exp}} \approx 1 \)), the fit of the data to a constant-flux model is good, but if \( s/\sigma_{\text{exp}} \) is significantly greater than 1, the fit is bad and the source is possibly variable. Plotted in Fig. 6 are examples of three different types of light curves. In the top panel (UV Aur), \( s/\sigma_{\text{exp}} \approx 1 \), and we
find a variability upper limit of \( s = 2.7 \text{ mmag} \). Most light curves in our survey fall into this category, and a list of the variability upper limits is given in Table 4. In the middle panel, we present the other extreme – a light curve of the well-known flickerer CH Cyg (e.g. Mikolajewski et al 1990a; Hoard 1993; Rodgers et al. 1997; Ezuka, Ishida & Makino 1998). For this light curve we find \( s/s_{\text{exp}} = 19.4 \), an unequivocal detection of variability. We did not find any new objects with this level of variability. An analysis of the variability properties of the five previously known, large-amplitude flickerers is given by Sokoloski et al. (in preparation). The bottom panel of Fig. 6 shows a marginal detection of flickering in the light curve of survey object CM Aql. In this case, \( s/s_{\text{exp}} = 1.4 \), and we are at or near our limits of detectability. Because of its small amplitude, this variability in this light curve could possibly be due to some unidentified systematic error. Measured and expected variances for the marginal detections of variability are listed in Table 5.

4.2 Periodic variability

The main tool we used to search for periodic variability was Fourier analysis of the light curves. In the discussion that follows, we consider a light curve that is simply a series of source count values (i.e., not ratios of source and comparison star count values), but the results apply for differential light curves as well. Our observations consisted of data points that were at least approximately evenly spaced, so we were able to use a simple discrete FFT routine for this analysis.

Consider a power spectrum constructed using the Leahy et al. (1983) normalization:

\[
P_j = \frac{2}{C_{\text{tot}}} |a_j|^2, \quad j = 0, \ldots, \frac{N}{2},
\]

where \( C_{\text{tot}} = \sum_{k=0}^{N-1} c(k) \) is the total number of source counts in a light curve, \( c(k) \) is the number of source counts in exposure \( k \), and the \( a_j \) are the Fourier amplitudes for the set of frequencies \( \nu_j = j/(N\Delta t) \):

\[
a_j = \sum_{k=0}^{N-1} c(k) e^{2\pi i j k/N}, \quad j = \frac{N}{2}, \ldots, \frac{N}{2} - 1
\]

(\( \Delta t \) is the time between data points). Note that \( a_0 = C_{\text{tot}} \). With this normalization, the average value of the power from a time series of purely Poisson noise is 2 (see Appendix A). If a light curve consists of a constant plus pure Poisson noise, then the underlying noise in the power spectrum, normalized as defined above, is distributed like \( \chi^2 \) with two degrees of freedom (van der Klis 1989; see Groth 1975 for derivation). One can therefore integrate the \( \chi^2 \) distribution to find the probability that a noise power will exceed the power level \( P \) in a given frequency bin:

\[
Pr(P_{\text{noise}} > P) = \frac{1}{2} \int_0^P e^{-y/2} dy = e^{-P/2}.
\]

Many other types of noise also produce a \( \chi^2 \) distribution of the noise powers (van der Klis 1989). In the general case of single or multiple noise sources which are normally distributed, the distribution function of noise powers can be written as

\[
f(y) = \frac{1}{P} e^{-y/P}.
\]

**Figure 6.** Example light curves showing, from top to bottom, a non-detection, a clear detection, and a marginal detection of rapid variability.
### Table 4. Variability upper limits.

| Name     | Date       | $s_{exp}$ | $s$ | Max Sine Amplitude | Period Range |
|----------|------------|-----------|-----|--------------------|--------------|
|          | (m/d/yr)   | (mmag)    | (mmag) | (mmag) | (min)         |
| AX Per   | 1/23/98    | 2.8       | 3.2  | 4.1               | 3.9–78.6     |
|          | 9/15/98$^a$ | 1.9       | 2.6  | 1.9               | 2.2–88.9     |
| V 741 Per| 8/22/98    | 2.4       | 2.8  | 3.2               | 3.5–45.6     |
| S 32     | 3/13/97$^b$ | 7.0       | 8.2  | 13                | 3.1–27.0     |
|          | 9/14/98$^a$ | 2.7       | 3.2  | 3.8               | 3.2–45.0     |
| UV Aur   | 11/2/97    | 2.7       | 2.7  | 1.9               | 1.8–62.7     |
| TX CVn   | 3/13/97$^b$ | 3.2       | 4.4  | 4.7               | 2.9–63.5     |
| RW Hya   | 2/18/97    | 3.4       | 4.2  | 3.6               | 1.8–41.2     |
| BD-21.3873 | 5/14/97   | 3.1       | 3.5  | 4.6               | 3.8–40.5     |
|          | 5/31/98    | 4.7       | 6.1  | 7.3               | 3.0–36.2     |
| AG Dra   | 6/7/97     | 3.9       | 6.3  | 4.7               | 1.6–66.5     |
|          | 7/23/98    | 5.4       | 5.8  | 4.0               | 2.7–92.9     |
| HD 154791 | 8/4/97     | 9.7       | 10.4 | 4.6               | 1.1–96.9     |
| Hen 1341 | 6/28/98    | 3.5       | 3.1  | 3.1               | 3.1–46.6     |
| AS 289   | 5/31/98    | 6.2       | 7.7  | 9.8               | 3.7–51.9     |
| YY Her   | 5/14/97    | 5.4       | 5.3  | 4.0               | 2.5–76.9     |
| AS 296   | 8/21/97    | 2.3       | 2.4  | 2.5               | 3.8–61.4     |
| S 149    | 5/15/97    | 3.5       | 3.8  | 3.8               | 2.8–44.7     |
|          | 8/20/98    | 3.6       | 3.4  | 2.5               | 2.6–91.5     |
| UV Aur   | 11/2/97    | 2.7       | 2.7  | 1.9               | 1.8–62.7     |
| TX CVn   | 3/13/97$^b$ | 3.2       | 4.4  | 4.7               | 2.9–63.5     |
| RW Hya   | 2/18/97    | 3.4       | 4.2  | 3.6               | 1.8–41.2     |
| BD-21.3873 | 5/14/97   | 3.1       | 3.5  | 4.6               | 3.8–40.5     |
|          | 5/31/98    | 4.7       | 6.1  | 7.3               | 3.0–36.2     |
| AG Dra   | 6/7/97     | 3.9       | 6.3  | 4.7               | 1.6–66.5     |
|          | 7/23/98    | 5.4       | 5.8  | 4.0               | 2.7–92.9     |
| HD 154791 | 8/4/97     | 9.7       | 10.4 | 4.6               | 1.1–96.9     |
| Hen 1341 | 6/28/98    | 3.5       | 3.1  | 3.1               | 3.1–46.6     |
| AS 289   | 5/31/98    | 6.2       | 7.7  | 9.8               | 3.7–51.9     |
| YY Her   | 5/14/97    | 5.4       | 5.3  | 4.0               | 2.5–76.9     |
| AS 296   | 8/21/97    | 2.3       | 2.4  | 2.5               | 3.8–61.4     |
| S 149    | 5/15/97    | 3.5       | 3.8  | 3.8               | 2.8–44.7     |
|          | 8/20/98    | 3.6       | 3.4  | 2.5               | 2.6–91.5     |

$^a$The timing errors are larger than usual for observations done in 1998 September because the high-precision WWVB clock was broken. For these observations, the time between integration starts is uncertain by up to a few seconds.

$^b$On 1997 March 13, incorrect time stamps were recorded in the image headers. The timing for this date is therefore only approximate.

### Table 5. Candidate variable systems.

| Name     | Date       | Filter | Fractional Variation | s$_{exp}$ | $s$ | sl$_{exp}$ | Power Spectrum | Max. Sine Amplitude | Period Range |
|----------|------------|--------|----------------------|-----------|-----|----------|-----------------|---------------------|--------------|
| EG And   | 1/17/97    | U      | 3.7                  | 3.8       | 1.0 |          | Low-frequency power present |
|          | 7/9/97     | U      | 3.2                  | 4.7       | 1.5 |          | Low-frequency power present |
|          | 7/11/97    | B      | 3.7                  | 3.5       | 0.9 |          | Low-frequency power present |
|          | 9/16/98    | U      | 2.8                  | 6.7       | 2.4 |          | Low-frequency power present |
|          | 9/14/98$^a$ | U      | 3.9                  | 5.4       | 5.8 |          | Low-frequency power present |
|          | 8/22/98    | B      | 2.5                  | 2.4       | 2.9 | 0.9       | Low-frequency power present |
|          | 7/1/98     | B      | 2.5                  | 5.5       | 5.1 | 2.0       | Low-frequency power present |
|          | 7/1/98     | B      | 2.5                  | 5.5       | 5.1 | 2.0       | Low-frequency power present |
|          | 7/1/98     | B      | 2.5                  | 5.5       | 5.1 | 2.0       | Low-frequency power present |
|          | 7/1/98     | B      | 2.5                  | 5.5       | 5.1 | 2.0       | Low-frequency power present |

$^a$Timing errors are larger than usual on this date, because the high-precision WWVB clock was broken.

$^b$Too few data to compute a meaningful power spectrum.
so that a more general expression for the probability that a noise power will exceed the power level \( P \) in a given frequency bin is

\[
\Pr(P_{\text{noise}} > P) = \frac{2}{P} e^{-\frac{P}{\bar{P}}} dy = e^{-\frac{P}{\bar{P}}}
\]

(22)

(Groth 1975; Scargle 1982), where \( \bar{P} \) is the average noise power near the frequency \( v_j \).

When examining an entire power spectrum, however, we are no longer asking about the chance of a noise power exceeding a given power \( P \) in a particular frequency bin, but instead the chance of a noise power exceeding \( P \) in any bin. Since the probability that the power in a given frequency bin will not reach the level \( P \) is \( 1 - e^{-\frac{P}{P_{\text{bin}}}} \), the probability that none of the points in the power spectrum will reach power \( P \) is \( (1 - e^{-\frac{P}{P_{\text{bin}}}})^n \), where \( n \) is the number of frequency bins. The analogous expression to equation (22) for a multiple frequency bin search is therefore

\[
\Pr(P_{\text{noise}} > P) = 1 - (1 - e^{-\frac{P}{P_{\text{bin}}}})^n,
\]

(23)

where \( \Pr(P_{\text{noise}} > P) \) is the probability that at least one of the noise powers will exceed \( P \). Note that in the limit where \( e^{-\frac{P}{P_{\text{bin}}}} \) is small, this probability for obtaining a noise power greater than \( P \) approaches the more intuitive \( n \Pr'(0) \times e^{-\frac{P}{P_{\text{bin}}}} \).

If a power spectrum computed from one of our survey light curves contained a peak that had less than a 5 per cent chance of having been produced by statistical noise, then that observation was flagged as a potential detection of periodic variability. In other words, if \( \Pr(P_{\text{noise}} > P) < 0.05 \), then there was a 95 per cent chance that a peak in a power spectrum was due to intrinsic source variability. By choosing a confidence level of 95 per cent for the detection threshold, our set of light curves could have produced several spurious detections. This fairly low detection threshold was selected so that real signals were unlikely to be missed, and because follow-up observations could be performed fairly easily (e.g., as were done for Z And; see Sokoloski & Bildsten 1999).

Whereas one can easily evaluate the likelihood that a detected power-spectrum peak is due to intrinsic source variability using the expressions above, the absence of a statistically significant peak is slightly more difficult to interpret. To see what sort of upper limits we can place on the amplitude of a periodic signal, if no significant power-spectrum peak is present, we calculate our sensitivity below, based on the treatment of this subject in van der Klis (1989).

The smallest-amplitude signal to which we are sensitive corresponds to a power \( P_{\text{sensitive}} = P_{\text{det}} - P_{\text{exceed}} \), where \( P_{\text{det}} \) is the minimum power for a secure detection of true source variability, and \( P_{\text{exceed}} \) is a low value that is very likely to be exceeded by a noise power. Setting the probability in equation (23) to a small number \( \epsilon \), we get \( P_{\text{det}} = - \frac{1}{\bar{P}} \ln[1 - (1 - e^{-\frac{P}{P_{\text{bin}}}})] \). Setting the probability in equation (22) to a large value \( 1 - \delta \), gives \( P_{\text{exceed}} = - \bar{P} \ln(1 - \delta) \). Putting these two expressions together, we find

\[
P_{\text{sensitive}} = \bar{P} \ln \left[ \frac{1 - \delta}{1 - (1 - e^{-\frac{1}{\sqrt{n_{\text{bin}}}}})} \right],
\]

(24)

with \( 1 - \delta \) and \( 1 - \epsilon \) both taken to be large (i.e., close to 1). It can be shown that the amplitude, \( A \), of a sinusoidal signal is related to the square of the Fourier amplitude for the bin containing the signal frequency by the expression

\[
\langle a_j \rangle^2 = \alpha \frac{1}{4} A^2 N^2,
\]

(25)

where \( \alpha \) has an average value of 0.77 and depends upon the location of the signal frequency in the frequency bin (van der Klis 1989). Substituting \( \langle a_j \rangle^2 = (P_{\text{sensitive}} C_{\text{tot}})^2 \) (from equation 18, for the Leahey normalization) and solving for \( A \), we find

\[
A_{\text{sensitive}} = 1.14 \frac{\sqrt{C_{\text{tot}}}}{N} \ln \left[ \frac{1 - \delta}{1 - (1 - e^{-\frac{1}{\sqrt{n_{\text{bin}}}}})} \right].
\]

(26)

Plugging in some typical numbers and taking \( 1 - \delta = 1 - \epsilon = 0.95 \), we find that in theory we are sensitive to sinusoidal signals with a fractional amplitude

\[
\frac{A_{\text{sensitive}}}{\bar{c}} = 0.001 \left( \frac{C_{\text{tot}}}{5 \times 10^7} \right)^{-1/2},
\]

(27)

for \( N = 200 \) and \( n_{\text{bin}} = 100 \) (recall that \( \bar{c} \) is the mean value of the number of source counts, \( c \), from a series of measurements). This fractional amplitude is roughly equal to 1 mmag.

Since the power of a sinusoidal signal with a given amplitude depends upon the location of the signal frequency within a frequency bin, the signal amplitude to which we are sensitive is only approximately given by the expression above. Thus the best way to determine a signal amplitude upper limit when there are no significant peaks in the power spectrum is through simulations. For each light curve, we therefore added sinusoidal variations with a range of amplitudes, frequencies, and phases to the data, and computed the power spectra. The trial frequencies ranged from the Nyquist value to \( 3/\fractot \) for each light curve, where \( \fractot \) is the total length of a light curve. Using \( 10^4 \) realizations for each trial amplitude (100 trial frequencies, and 100 phases for each frequency), we took the signal amplitude upper limit to be that which produced a 95 per cent confidence level detection 95 per cent of the time. The periodic variability upper limits for each object for which no significant peaks were present in the power spectrum are listed in Table 4.

### 4.3 Sources of error

To determine the amount of systematic error in our differential photometry, we examined the comparison stars in multiple fields to determine whether there was a systematic excess variance beyond that expected from the CCD equation and scintillation. For star \( m \) in image \( i \) (out of \( N \) images in an observation), the expected fractional variance is given by

\[
x_{\text{exp},m}^2(i) = \left[ \frac{\sigma_{\text{CCD},m}(i)}{c_{\text{exp},m}(i)} \right]^2 + \sigma_{\text{scint},m}^2.(28)
\]

where \( \sigma_{\text{CCD},m}(i) \) is the variance from equation (6) for star \( m \) in image \( i \), \( c_{exp}(i) \) is the number of stellar counts for star \( m \) in image \( i \), and \( \sigma_{\text{scint},m} \) is the scintillation given by equation (10). If the ratio of the fluxes of two stars \( l \) and \( m \) is formed to remove the effects of clouds and seeing variations, the expected fractional variance of this ratio is

\[
x_{\text{exp},l\text{m}}^2(i) = x_{\text{exp},l}^2(i) + x_{\text{exp},m}^2(i). (29)
\]

The average expected fractional variance for this flux ratio for the entire observation is

\[
x_{\text{exp},lm}^2 = \frac{\sum_i \frac{1}{x_{\text{exp},lm}^2(i)} x_{\text{exp},lm}^2(i)}{\sum_j 1/x_{\text{exp},lm}^2(j)} = \frac{N}{\sum_j 1/x_{\text{exp},lm}^2(j)}. (30)
\]

For every possible pair-wise combination of comparison stars in the test fields, the flux ratio was formed, the expected fractional variance from the CCD equation and scintillation was calculated,
and the actual fractional variance of the flux ratio was measured. By solving a simple system of equations that had the same form as equation (29), we could then obtain the variance due to systematic errors for each star individually.

In most cases, little systematic error was found. Furthermore, the examination of measured versus expected rms variation for constant-brightness field stars allowed us to come up with a criterion for identifying low-level, flickering-type source variability. The constant comparison stars generally had variances that were within 40 per cent of the expected values (both measured and expected variances were typically on the order of a few mmag). Therefore any symbiotic in the survey with $s/s_{\text{exp}} \geq 1.4$ was considered to have a potential detection of variability.

Looking at the comparison-star fluxes with respect to each other in each field also allowed us to identify any variable comparison stars and exclude them from the analysis. Data from a new pulsating A-type star with a 28.5-min period that was discovered in this way, as well as several other serendipitous discoveries, are presented in (Sokoloski et al., in preparation).

As mentioned above, we found that in most cases, systematic error was negligible. However, there were a few instances in which problems arose. The first problem we found was a result of the poor centroiding performed in the IRAF-based IDL routine ‘cntrd’. The centroiding problems are evident from the large scatter in the difference between stellar positions output from ‘cntrd’ for a series of images of the same field. Improved centres were obtained by assuming the PSFs had a roughly bivariate Gaussian shape, and fitting the PSFs with this function with the x and y centres as free parameters. Fig. 7 shows a differential light curve for comparison stars in the field of BX Mon on 1997 February 26, first before, and then after the centring improvement.

A second source of error, ‘pixelization noise’, is relevant only for small extraction apertures. This error arises because of imperfect estimation of the fraction of counts that should be included from a bin that falls only partially within the extraction region. For large apertures, there are relatively few edge bins compared to bins that are fully within the aperture, and the effect of pixelization is small. To estimate the magnitude of pixelization noise for various aperture sizes, and for stellar PSF profiles of various widths, we created very finely sampled Gaussian stellar profiles, and binned them as they would be on our CCDs, with the true centre of the profile placed at $2.5 \times 10^5$ different positions in a bin. We then performed circular-aperture photometry with our software for each different PSF position. In Fig. 8, several contour plots show the change in extracted flux as a function of position of the PSF centre within a bin. In Fig. 9 is plotted the fractional variation in the extracted fluxes as a function of extraction aperture for various Gaussian profile widths.

Furthermore, there appears to be a slight positional dependence of the PSF (at least for CCD 2), which can be seen by comparing the x and y width of the Gaussian fits for the different stars in a field. For observations with stable seeing, this PSF difference is not a problem. If the seeing changed significantly during an observation, however, then one of the assumptions of our differential photometry was violated, and the light curve could exhibit variability that was either directly or inversely correlated with seeing. It is also possible that excess variance in the final ensemble average light curve could be due to some cosmic rays within the programme star extraction region. We were more cautious about removing data with suspected cosmic ray hits on the programme star than we were with data in which the comparison stars were affected, in order to avoid removing real variability. However, the numerous light curves for which we do not find excess variability in the programme star indicate that this is probably not a significant issue.

In a few observations, a correlation between the differential light curve and a measure of the seeing, the position of the stars on the chip, features seen in the raw light curves of all stars in the field, the background, or some other house-keeping information indicated the possible presence of some systematic error. Likely candidates for the source of the error include differences in the PSFs, blended images, differential extinction, or positional dependences of gain or bias features (see Gilliland & Brown 1988, who find that colour and position corrections matter). Any data that were clearly affected by systematic error (usually during extremely poor weather) were not used, and some questionable cases are discussed later. For most observations, however, all of the above effects were small compared to statistical noise sources such as Poisson noise due to counting statistics and read noise.

5 RESULTS

5.1 Upper limits

For 25 of the 35 objects in our survey, no variability, either periodic or aperiodic, was detected. The fractional rms variations ($s$) for these objects are listed in Table 4. Some representative light curves and corresponding power spectra are shown in Fig. 10. The value of $s$ for these 25 objects ranged from 2.4 to 10.4 mmag, giving $s/s_{\text{exp}} \leq 1.4$ (where $s_{\text{exp}}$ is the rms fractional variation expected from Poisson statistics and scintillation, defined in equation 15) for all but one observation, which we discuss below. The upper limits on the amplitude of any periodic oscillations present in these data fall in approximately the same range of a few to 10 mmag, or less than a 1 per cent flux variation (see Table 4). As discussed in Section 4.2, the oscillation-amplitude upper limits correspond to the amplitude of a sinusoidal signal which, when injected into the data at a range of periods and phases, produced a formal 95 per cent confidence detection 95 per cent of the time.

Two of the observations presented in Table 4 as upper limits actually contained some low-level variability, which we do not believe to be due to intrinsic source variations. The power spectrum from the 1998 September 15 observation of AX Per has a peak above the formal signal-detection level. However, significant low-frequency power was also seen in some of the comparison stars, as well as in AX Per, and so systematic effects were probably present. In the 1997 June 7 observation of AG Dra, which was done with only a single comparison star, the flux appears related to the position of the star on the chip, and the variation is therefore also believed to be due to a systematic effect. In both cases, a second observation showed no variability.

The main result for the 25 objects listed in Table 4, and therefore one of the main results from our 35-object survey, is that although most SS contain accreting WDs, as in CVs, they generally do not show CV-like optical flickering. For over 70 per cent of the symbiotics in this survey, the amplitude of any rapid optical variability is constrained to just a fraction of a per cent.

5.2 New candidate flickerers

In four systems, evidence for aperiodic rapid variability was found for the first time. We consider an observation to contain a potential detection of rapid variability if $s/s_{\text{exp}} \geq 1.4$, and the variations are...
not correlated with any of our house-keeping data. Since all of these measurements are near our detection limits, however, they should be considered rather uncertain, and further observations are needed to confirm the presence of flickering in these objects. The candidate variable systems are discussed individually below. Their expected and measured fractional rms variations are listed in Table 5.

5.2.1 EG And

EG And was observed on four occasions, three times with a $U$ filter, and once with a $B$ filter. In two of the $U$-band observations, on 1997 July 9 and 1998 September 16, there is evidence for low-level flickering. The measured variance was 50 per cent above the expected level on 1997 July 9, and more than twice the expected

---

Figure 7. A particularly extreme example of the improvement in our light curves once a centring correction was applied. These light curves were constructed from the eight comparison stars in the field of BX Mon on 1997 February 16, using an aperture radius of 2.9 arcsec.

Figure 8. Four examples of the extracted flux as a function of position of the stellar PSF centre in a bin. Plotted is the difference in flux from the mean value in units of mmag, for a Gaussian PSF with $\sigma_{\text{Gauss}} = 1.4$ bins. Note that the variation is smaller for larger extraction radius, $r$. 
The observation that produced the most variable light curve, on 1998 September 16, however, was performed using the smaller field CCD 5, which allowed only one reasonably bright comparison star. Moreover, this one bright comparison star was near a feature on the chip which introduced a slow rise in the comparison star flux as the star drifted toward the feature. There does not appear to be a correlation between the position of the comparison star and the rapid flux variations in the light curve, but the presence of this chip feature does introduce another reason for caution when interpreting these results. Plots of the four EG And light curves are shown in Fig. 11. The power spectrum from 1998 September 16 contained significant low-frequency power spread over several frequencies. No statistically significant peaks were present in the power spectra from the other three observations.

To illustrate the difficulty with interpretation of these observations, Fig. 12 shows, for 1998 September 16, the flux ratio of EG And flux versus the main comparison star, the flux ratio of EG And flux versus the sum of two very faint stars in the field, and the flux ratio of the main comparison star versus the sum of the two faint stars. For a high-confidence-level detection, one would like to see significant and correlated variability in both the first and second ratios, but not the third. The measured variance is, in fact, more than twice the expected variance ($\sigma_{\text{meas}}^2 = 2.4$) for the first ratio, the measured variance is approximately 40 per cent higher.
than that expected from a constant source for the second ratio ($s/s_{\text{exp}} = 1.4$), and the two quantities are nearly the same for the third ratio ($s/s_{\text{exp}} = 1.1$). For this object, it is also interesting to note that the very flat $B$ light curve of 1997 July 11 is only two nights away from a $U$ observation that shows hints of variability.

5.2.2 BX Mon

Our first observation of BX Mon, on 1997 January 18, produced only a small amount of low-quality data, so we re-observed this object on 1997 February 16. On that date, we found a significant excess variance. The rms fractional variation is 2.7 times higher than expected from Poisson fluctuations and scintillation. No comparison stars showed similar variations, and the variations in BX Mon were evident no matter what combination of comparison stars was used. Unfortunately, there is some chance that these variations are due to atmospheric changes. A plot of seeing as a function of time looks similar to the BX Mon light curve in places, although the two quantities are not strictly correlated. The 1997 February 16 light curve for BX Mon, and a measure of the PSF width (from a different star in the same field) during the observation, are shown in Fig. 13. The seeing measure plotted in this figure is the second moment of the distribution of counts within the aperture used.

Follow-up observations were performed in 1997 March, April and November, but the results for this object remain inconclusive. Flickering was possibly detected in a $U$-band observation on 1997 March 12 ($s/s_{\text{exp}} = 1.9$), but on this night some of the comparison stars also showed excess variability. Variations were not detected in any other observations. Example light curves, from 1997 March 12 and 1997 November 1, are shown in Fig. 14.

5.2.3 CM Aql

We observed CM Aql once, on 1998 September 16, with a $B$ filter, using CCD 5. The measured fractional variation is just 35 per cent higher than expected for this observation (i.e., $s/s_{\text{exp}} = 1.35$). However, the small variations that are present (see Fig. 15) do not appear related to any of our house-keeping data, and the observation was made in good weather conditions. This situation is in contrast to other borderline case observations with $s/s_{\text{exp}} < 1.4$ (e.g., TX CVn, CI Cyg and AS 360), which were made under poor weather conditions or do not show any point-to-point correlated variations. Further observations are required to determine whether this flickering is intrinsic to CM Aql. It is possible that the higher sensitivity CCD 5 requires a more thorough study of systematic effects.

5.2.4 BF Cyg

We found low-amplitude variability in BF Cyg on three separate occasions, separated by more than a year. This variability does not appear to be correlated with seeing or any other house-keeping data, and it was not seen in any of the five comparison stars. In each observation, the measured variance was more than twice that expected from Poisson variations and scintillation ($s/s_{\text{exp}} > 2$), and so this source is a prime candidate for follow-up study. All observations were done with the $B$ filter. The light curves are presented in Fig. 16.

5.3 Previously known flickering symbiotics

Included in our survey were five well-known flickering symbiotics: Mira AB, MWC 560, T Crb, RS Oph and CH Cyg. We confirmed the presence of rapid optical variability in all five systems, and

![Figure 11](https://academic.oup.com/mnras/article-abstract/326/2/553/1005925)

**Figure 11.** Light curves from the four observations of EG And are shown. Statistically significant variability is seen in the second and third $U$-band light curves, whereas the $B$-band light curve is consistent with an assumption of constant flux.
recorded a marked change in the flickering properties of both T CrB and CH Cyg over the course of the survey. A full analysis of these observations is presented elsewhere (Sokoloski et al., in preparation), but example light curves for each of the large-amplitude flickerers are shown in Fig. 17. These light curves are shown, at least in part, to emphasize the difference between these five systems and the other 30 objects in the sample. Note that the ordinate for each plot in Fig. 17 spans 0.5 mag, whereas the 25 objects for which no rapid variations were detected are constant to within a few mmag. The four new candidate flickerers vary at a level of only a few tens of mmag.

5.4 Future work

Although for the faintest targets a larger telescope would have improved our sensitivity, in most cases we were more limited by the capabilities of the CCD detectors than the telescope collecting area. The limitations of the CCDs were especially apparent for the bright objects, objects with bright comparison stars, or objects in sparse fields. When we observed fields containing bright stars, integration times were limited by CCD non-linearity and saturation, and the duty cycle of an observation was sometimes low. To improve measurements of low-amplitude rapid variability,
one would like to have a CCD with a larger field of view and faster readout times. Masking techniques in which part of the CCD is read out while another part is exposed would greatly improve the efficiency of this type of observation. A larger field would allow for additional bright stars nearby, this improvement is absolutely essential for differential photometry. For other fields, having a larger number of comparison stars would allow for PSF fitting and a better understanding of systematic. In addition, the ideal detector would have either an adjustable gain, or a gain that was high enough to allow for photometry on a field of stars with a large dynamic range of brightnesses. One would like to always have the option of integrating to the scintillation limit before saturating a star or reaching the non-linear regime. With such a detector, and observations made at low airmass, one could probe much lower levels of variability (<1 mmag), as well as shorter time-scales.

6 DISCUSSION

Our survey has revealed new hints of rapid variability in four symbiotics: EG And, CM Aql, BX Mon and BF Cyg. Our main result, however, is that most symbiotics do not vary on a time-scale of minutes, down to a level of mmag. Previous authors have noted this apparent general lack of rapid variability in symbiotics (e.g. Walker 1977; Dobrzycka et al. 1996). Our work broadens and strengthens this conclusion. We have placed tight upper limits on both aperiodic and periodic variability for 25 of the 35 objects observed. We also performed extensive observations of the five previously known, large-amplitude flickerers, which are found to be rare among symbiotics. These observations, as well as serendipitous discoveries of five new variable stars and results for the magnetic symbiotic Z And, are presented in separate papers (Sokoloski & Bildsten 1999; Sokoloski et al., in preparation).

This survey of optical variability has been carried out primarily in the B band, with some supplementary observations done in U. The B-band optical flux from symbiotics originates from several sources, including the red giant, recombination radiation from the nebula (which is pumped by the far-ultraviolet and soft X-ray emission from the hot component), and possibly some direct emission from a disc or the hot star itself. For comparison, the optical flux in CVs is dominated by emission from the accretion disc, and in supersoft sources the optical light is primarily from an irradiated disc. We discuss below the differences in optical variability properties between symbiotics and other accreting-WD binaries, differences among the SS, and what these variability properties might be telling us about the underlying sources of light.

One of the important distinctions between CVs and symbiotics is that in many symbiotics, the high hot-component luminosity indicates that material must be burning quasi-steadily on the surface of a WD, either because the accretion rate is in the steady-burning regime, or as residual burning from a past outburst (Paczynski & Rudak 1980; Iben 1982; Mikolajewska & Kenyon 1992a,b; Sion & Starrfield 1994). Some of the far-ultraviolet and soft X-ray flux from this persistent nuclear burning is reprocessed into the optical by the nebula. Since the flux from the nuclear burning does not change on short time-scales, and the nebula itself is unlikely to introduce rapid variability, the nuclear burning produces an extra contribution to the optical flux in symbiotics that is not variable on short time-scales. Therefore the amplitude of any rapidly variations from the accretion are reduced compared to similar variations in CVs. In supersoft sources, as in symbiotics, far-ultraviolet and soft X-ray emission from nuclear burning on a WD is reprocessed into the optical. In supersoft sources, however, the reprocessing occurs primarily in a flared accretion disc instead of an extended nebula (Popham & DiStefano 1996), and disc-rim fluctuations could introduce an additional source of rapid optical variability (Meyer-Hofmeister et al. 1998).

Thus the amplitude of rapid optical variability in symbiotics and other accreting-WD binaries is linked to the presence or absence of a physical process (nuclear burning) that profoundly affects the binary. Nuclear burning on the surface of a WD produces much more power than accretion alone, and the presence of such burning may be closely related to the outbursts in classical symbiotics. In one model for these outbursts, the months-to-years-long events are due to the expansion of the WD photosphere in response to an increase in the accretion rate on to the WD (see Mikolajewska & Kenyon 1992a,b for a review of these models). However, this phenomenon, which is similar to that proposed to explain the optical rises and X-ray dips of the supersoft sources (e.g. Kahabka 1998), can only occur if the WD is burning material quasi-steadily. Also, there is another reason why it is critical to understand how the accumulated fuel is burning. Symbiotics might be progenitors of Type Ia supernovae, but this depends on their ability to increase in mass as they accrete. The more fuel that is burned in steady-state, the better for increasing the mass of the WD, since large classical nova outbursts can actually excavate the WD. The connection between the amplitude of rapid optical variability and the presence of nuclear burning on the WD is explored in greater detail in Section 6.3.

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Figure 16. $B$-band light curves for BF Cyg.

Figure 17. Representative $B$-band light curves for the previously known flickering symbiotics. These objects form a subclass of symbiotics that are clearly distinct from the majority of systems, in which rapid optical variability either has very low amplitude or is undetectable.
6.1 Magnetism in the accreting white dwarfs

In our survey of 35 symbiotics, we found one new clearly magnetic system (Z And; see Sokoloski & Bildsten 1999). For 25 objects, we detected no rapid variability, and we place upper limits ranging from 1.9 to 13 mmag on periodic oscillation amplitudes in these objects. The absence of a detected periodic signal in these 25 systems, however, does not necessarily mean that they are not magnetic. The amplitude of the Z And oscillation during quiescence was extremely small (roughly 1 mmag peak-to-peak), and the presence of a similar-sized oscillation in the other objects is not ruled out by any of the upper limits in Table 4. In fact, the Z And oscillation was discovered only because the object was fortuitously observed during an outburst of the system, during which the oscillation amplitude was larger. It is worth noting here that estimates of the luminosity of the WD in Z And gives values of 500–2000 L⊙ (Mürset et al. 1991; Dobrzycka et al. 1996, and references therein), indicating that nuclear burning must be occurring on the surface of the WD. Given our discussion above concerning the effect of nuclear burning on the amplitude of rapid optical variations, it is not surprising that the amplitude of the Z And oscillation is much smaller than the corresponding optical modulations seen in intermediate polars.

Searching for oscillations is more subtle in the flickering objects, and we tackle this problem in a separate paper (Sokoloski et al., in preparation). Therefore, here we place only a lower limit on the fraction of symbiotics in our sample that contain magnetic WDs. Since we detected one magnetic system out of 32 possible WD systems (three symbiotics in our sample have either main-sequence-star or neutron-star hot components), at least 3 per cent of the WD systems in our sample are strongly magnetic. This number should be compared to 2 per cent for field WDs (53 out of 2249; Anselowitz et al. 1999), and 5–10 per cent for WDs in CVs (Warner 1995). Although the statistics are obviously too small to determine the true magnetic fraction for SS, our results are consistent with this fraction being higher than it is in the field, as with CVs.

6.2 Flickering

Our survey did not yield any new strong (s = 20 mmag) flickerers. For most objects, the upper limit we have placed on aperiodic variability (flickering) is a few mmags (see Table 4). Weak flickering (at the ≤10 mmag level) was possibly detected in a few of our survey objects, which we discuss in Section 5. Unfortunately, flickering at this low level is difficult to attribute to the source, as many observational systematics can have a comparable amplitude. The new candidate flickerers are, however, clearly worth additional study.

By comparing the small fractional rms variations listed in Tables 4 and 5 with the large flickering amplitude of the five well-known flickering symbiotics shown in Fig. 17, it is apparent that the distribution of flickering amplitudes in symbiotics is bimodal: there are a few large-amplitude flickerers, but most symbiotics show little to no flickering. This is in sharp contrast to the CVs, where most show persistent flickering at a level of ≥100 mmag. The flickering light in CVs could come from several areas, including the inner accretion disc, the splash point, or the surface of the WD (Warner 1995; Bruch 1992). Moreover, these flickering sources contribute to different degrees in different object. However, no matter which specific origin, the power source is accretion, and flickering is prevalent in the CVs. We have found that flickering is much less prevalent in the symbiotics. Several possible explanations include: (a) the optical flux in most SS is dominated by light from the red giant, which does not change on short time-scales, (b) the nebula ‘washes out’ the flickering light, (c) most SS do not accrete through a disc, and the wind-fed accretion does not produce optical flickering, or (d) in SS with no, or only small-amplitude, rapid variations, much of the hot component light is from nuclear burning of accreted material, which is stable on a time-scale of minutes. We consider each of these possibilities below.

6.2.1 The red giant

We can rule out this simple explanation by comparing the red giants in the flickering and non-flickering symbiotics. If the red giants in the flickering symbiotics were systematically fainter, or of later spectral type, than the red giants in the non-flickering symbiotics, the contribution to the B-band flux from the red giant would be lower. This reduced contribution from the red giant could allow any variable emission from the hot component that might normally be hidden to be revealed.

In fact, there is no such systematic difference. Kenyon & Fernandez-Castro (1987) derive spectral types for the giants in 25 symbiotic binaries, and find most systems to be M2–5 III. Included in their study were three of the well-known large-amplitude flickerers (T CrB, CH Cyg and RS Oph), and two of our marginal flickering detection objects (EG And and BX Mon). The red giant in T CrB is found to be M4.1 ± 0.3 III, that in CH Cyg to be M6.5 ± 0.3 III, and that in RS Oph to be K5.7 ± 0.4 I-II. The red giant in EG And was found to have spectral type M2.4 ± 0.3 II, and the red giant in BX Mon was found to have type M4.6 ± 0.4 III. These giants are therefore all quite typical for symbiotics, except for that in RS Oph, which is actually earlier and brighter than average. Furthermore, if the contribution from the red giant was the main factor in determining the flickering amplitude, one would expect a more continuous distribution of amplitudes.

6.2.2 The nebula

Radio observations of thermal bremsstrahlung from the photo-ionized nebulae in SS indicate that typical sizes are usually less than 10^15 cm (Seaquist, Taylor & Button 1984). From UV line intensity ratios, densities in the nebula are estimated to be 10^5 to 10^10 cm^-3, and temperatures are on the order of 10^5 K (Kenyon 1986; Nussbaumer & Vogel 1987). The presence of the nebula could make flux modulation from either magnetic accretion or flickering more difficult to detect in SS.

The nebula can affect the rapid optical variability in two ways. Nebular reprocessing can hide some temporal variations from the hot component which originates in the FUV or higher energies by acting as a low-pass filter. In addition, non-variable or slowly varying optical emission from the nebula will reduce the amplitude of any rapid variability that might originate in the optical band, for example from an accretion disc. Rapid variations in the flux of ionizing photons could possibly be passed into the optical if the nebula is dense and radiation-bounded (i.e., if the ionized nebula is in the form of a single closed Strömgren region). Roughly speaking, if the nebula is radiation-bounded, far-ultraviolet photons are all absorbed in photoionization events. If the output of ionizing photons varies, then the size of the Strömgren region varies, and so does the amount of reprocessed optical light. If the nebula is dense enough at the boundary between the ionized and
neutral regions, the recombination time will be short, and rapid variations in the ionizing flux could in principle be propagated into the optical. Typical densities in the red giant winds that form the nebula can reach $\sim 10^{10} \text{cm}^{-3}$, giving a hydrogen recombination time of minutes. However, most SS nebulae are probably not radiation-bounded (Mürset et al. 1991). In addition, light travel time effects would cause any sharp temporal features to be smeared out, as this light would be reprocessed in parts of the nebula that are different distances away from the hot WD. Finally, if the reprocessing time in the nebula is long, then the rapid variability will not be passed along to the optical light, no matter whether the nebula is radiation-bounded or density-bounded (gas completely ionized so that some ionizing photons escape). The ionized nebula does not have as much effect on optical photons, so variability which originates in the optical should not be washed out, only possibly diluted. Given the above discussion about the difficulty of producing rapid variability from the nebular emission, we would expect the spectrum of the rapidly variable component of the large-amplitude flickerers (such as RS Oph) to reflect the physical origin of the variations, for example in an accretion disc, and not be dominated by nebular features.

6.2.3 Accretion disc or not?

An interesting question to ask is whether the amplitude of flickering in SS can tell us whether the accreted material’s final plunge on to the WD is via a disc or directly from the wind. The flickering in CVs is related to disc accretion, and Livio (1988) showed that discs might well form in wind-fed symbiotics. A flickering in CVs is related to disc accretion, and Livio (1988) plunge on to the WD is via a disc or directly from the wind. The flickering in SS can tell us whether the accreted material’s final variations, for example in an accretion disc, and not be dominated by nebular features.

6.2.4 Nuclear power versus gravitational power, and the relationship between flickering and outbursts

In their study of eight SS, Dobrzycka et al. (1996) note that the objects with lower hot-component luminosities, $L_{\text{hot}}$, seem more likely to flicker. Our study of 35 objects produced four new candidate small-amplitude flickering systems, but showed primarily that most SS do not flicker (i.e., most have variations of less than a few mmag). Could this wide-spread lack of large-amplitude flickering be due to the source of power in SS? A potential hint to the flickering puzzle can be found by considering the symbiotic recurrent novae, which clearly burn most of their fuel in outbursts. They are thus unlikely to have large nuclear-burning luminosities in quiescence. The expectation that these systems (between novae) are largely powered by gravitational energy release is consistent with the detected flickering. For example, at least three of the four symbiotic recurrent novae (RS Oph, T CrB, V1017 Sgr; we are not aware of observations of the fourth, V3890 Sgr) flicker, and these three systems also have $L_{\text{hot}} < 100 L_\odot$ (Dobrzycka et al. 1996). Moreover, the flickering amplitude in these systems is comparable to that seen in CVs (Walker 1977). The other strong flickerers are MWC 560, CH Cyg, and Mira. Both Mira and CH Cyg have low hot component luminosities ($L_{\text{hot}} < 10 \text{L}_\odot$). In MWC 560, the hot component is brighter, but the uncertainty in this quantity is large.

Generally speaking, it is clear that the objects with low $L_{\text{hot}}$ preferentially exhibit CV-like flickering. It is also the case that the objects with higher $L_{\text{hot}}$ generally either do not flicker, or have only small-amplitude flickering. An interesting speculation that follows from this observation is that any SS that are found to display large-amplitude flickering should eventually experience a nova.

A final bit of supporting evidence for the picture in which the amplitude of the rapid optical variations is reduced in SS that contain nuclear burning on a WD is the low amplitude of the coherent oscillation in Z And compared to the DQ Her systems. The optical light of the DQ Hers typically is modulated by about 10 per cent at the WD spin period (Warner 1995; Patterson 1994), but in Z And the modulation is only about 0.1 per cent (when the system is in quiescence). This modulation would be expected to be smaller than those seen in the DQ Her systems if there is a large additional source of relatively constant optical flux. Note that this argument is based on the assumption that the amount of pulsed optical flux from accretion on to a magnetic WD is intrinsically the same for the two types of systems, which may not in fact be the case.

6.3 More on nuclear burning

Most CVs are clearly powered by gravitational energy released in the process of accretion. In these low accretion-rate systems ($M < 10^{-9} M_\odot \text{yr}^{-1}$), the nuclear burning of the accreted material occurs via classical novae and very little fuel is burned between nova events. This should be contrasted with the supersoft sources, where the high luminosity and spectral fitting from ROSAT points to steady-state nuclear burning as the prime power source for their...
emission at all times (van den Heuvel et al. 1992). The required accretion rates for stable burning range from $M \approx 10^{-8} M_\odot \, \text{yr}^{-1}$ for a $M = 0.4 M_\odot$ WD to $M = 3 \times 10^{-7} M_\odot \, \text{yr}^{-1}$ for a $M = 1.2 M_\odot$ WD (Paczynski & Zytkow 1978; Fujimoto 1982).

The WDs in symbiotics are thought to accrete at a rate of $\sim 10^{-8} M_\odot \, \text{yr}^{-1}$. This rate is in the range that can produce steady burning, and therefore forces us to consider the importance of nuclear burning as an energy source in these systems. For accretion on to a WD, nuclear energy release exceeds that from gravity by a factor of $\sim 30$ (the ratio of the accretion energy, $GM/R \approx 100$–200 keV nucleon$^{-1}$, to the nuclear burning energy, 5 MeV per nucleon, is 2–3 per cent), so that even partial burning of the accreting fuel can prove important. Indeed, $L_{\text{hot}}$ is so high for many symbiotics that gravitational energy release cannot be the sole source of power, and burning must be occurring. Careful spectral analysis of the nebular emission lines in symbiotics is used to infer the luminosity, $L_{\text{hot}}$, of the hot component, which is modelled as either a star or the inner region of an accretion disc (Kenyon & Webbink 1984; Müssel et al. 1991). We show these $L_{\text{hot}}$ estimates, where available, in Table 3, along with other properties. Furthermore, some symbiotics have been detected with ROSAT as supersoft X-ray emitters (Müssel, Wolff & Jordan 1997). It is not clear, however, that this steady burning consumes all of the accreted fuel; possibly some is still being accumulated and burns in an outburst.

A key point to note here is that the nuclear-burning luminosity would not be expected to change on short time-scales such as minutes or hours. Hence a WD that is steadily burning the accreting material, and reprocessing the burning emission into the optical, cannot flicker rapidly at a high level. The thermal time in a steadily burning envelope at a depth denoted by the mass above it, $\Delta M$, is $t_{\text{th}} \approx (C_P T/E_{\text{nuc}})(\Delta M/M)$, where $C_P \approx 5k_B/2\mu m_p$ is the specific heat at constant pressure ($k_B$ is Boltzmann's constant, and $\mu = 1/2$ is the mean molecular weight), $T$ is the temperature in the envelope, and $E_{\text{nuc}} \approx 5 \times 10^{18} \text{erg g}^{-1}$ is the nuclear energy released by hydrogen burning. For a typical temperature in a marginally stable burning region of $T \approx 3 \times 10^7 \text{K}$, the expression above gives

$$t_{\text{th}} \approx 2 \times 10^{-3} \left( \frac{\Delta M}{M} \right). \quad (31)$$

For a 1.2-$M_\odot$ WD, this time is approximately 10 d, using $\Delta M = 3 \times 10^{-6} M_\odot$ from fig. 7 in Fujimoto (1982), and $M = 2 \times 10^{-7} M_\odot \, \text{yr}^{-1}$. This time-scale is shorter for more massive WDs, as $\Delta M$ decreases with the mass of the WD. The shortest possible time is thus for a near-Chandrasekhar-mass WD, and even then equation (31) gives a time-scale of about one day (for $M = 1.4 M_\odot$, $\Delta M = 4 \times 10^{-7} M_\odot$, and $M = 3 \times 10^{-7} M_\odot \, \text{yr}^{-1}$). So it appears that the thermal time at the location where the burning is occurring cannot get shorter than about a day.

In symbiotics, a significant amount of the nuclear burning flux can end up in the optical because of reprocessing in the nebula. Since this flux does not vary rapidly, and the nebula is unlikely to introduce rapid variations, any short-time-scale optical variations due to accretion are like to be hidden or reduced, as we have found. In the supersoft sources, high-energy photons from the nuclear burning can also be reprocessed into the optical, but in these systems it is the large, flared disc that is the site of the reprocessing (Popham & di Stefano 1996). Photometric observations with the required sensitivity are difficult to perform for most supersoft sources, since they are generally fainter in the optical than CVs or SS, but photometric studies have been done. Rapid optical variability was detected in the Galactic supersofts RX J0925.7–4758 (Clarkson et al., in preparation), RX J0019.8+2156 (Meyer-Hofmeister et al. 1998), 1E 0035.4–7230 (Crampton et al.; van Teeseling et al., 1998), and possibly several others as well. Meyer-Hofmeister et al. (1998) suggest that the variations in RX J0019.8–2156 are due to changes in the disc rim, where the nuclear-burning light is reprocessed. The rapid variations in some of the supersofts could also be due to CV-like flickering from the disc that has not been completely hidden by the nuclear-burning light. For information on the effect of nuclear burning in CVs, we can look at the short-period system T Pyx (P$_{\text{orb}} = 1.8$ h). T Pyx is believed to be burning material to a significant extent even in quiescence (Patterson et al. 1998). However, it does not have a nebula or other large reprocessing site where the high-energy photons can be converted to optical light, so the flux from the quasi-steady burning in T Pyx probably makes only a relatively small contribution to the optical flux. In fact, the optical light curves from this system show obvious large-amplitude flickering (Patterson et al. 1998), presumably from the accretion disc. So, in examining the relationship between the optical variability properties of SS and other WD accretors, we find that the presence or absence of nuclear burning on the WD can have an important effect, but that the nature of the reprocessing site is also relevant.

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REFERENCES

Angel J. R. P., Borra E. F., Landstreet J. D., 1981, ApJS, 45, 457
Anselowitz T., Matthews K., Sion E. M., McCook G. P., 1999, PASP, 111, 702
Belczynski K., Mikolajewska J., Munari U., Ivison R. J., Friedland M., 2000, A&A, 146, 407
Bevington P. R., 1969, Data Reduction and Error Analysis for the Physical Sciences. McGraw-Hill, New York
Bruch A., 1992, A&A, 266, 237
Bruch A., Duschl W. J., 1993, A&A, 275, 219
Ciardullo R., Bond H. E., 1996, AJ, 111, 2332
Crampton D., Hutchings J. B., Cowley A. P., Schmidtke P. C., 1997, ApJ, 489, 903
Dobrzycka D., Kenyon S. J., Milone A. A. E., 1996, AJ, 111, 414
Downes R. A., Keyes C. D., 1988, AJ, 96, 777
Ezuka H., Ishida M., Makino F., 1998, ApJ, 499, 388
Fritz T., Bruch A., 1998, A&A, 332, 586
Fujimoto M. Y., 1982, ApJ, 257, 767
 Gilliland R. L., 1992, in Howell S. B., ed., ASP Conf. Ser. Vol. 23, Astronomical CCD Observing and Reduction Techniques. Astron. Soc. Pac., San Francisco, p. 68
Dobrzycka D., Kenyon S. J., Milone A. A. E., 1996, AJ, 111, 414
Downes R. A., Keyes C. D., 1988, AJ, 96, 777
Ezuka H., Ishida M., Makino F., 1998, ApJ, 499, 388
Fritz T., Bruch A., 1998, A&A, 332, 586
Fujimoto M. Y., 1982, ApJ, 257, 767
 Gilliland R. L., Brown T. M., 1988, PASP, 100, 754
Gilliland R. L., Brown T. M., 1992, PASP, 104, 582
Groth E. J., 1975, ApJS, 29, 285

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APPENDIX A: AVERAGE POWER OF POISSON NOISE WITH THE LEAHY NORMALIZATION

We relate the fractional rms variation of a light curve to the average power in a power spectrum that has been normalized according to the prescription of Leahy et al. (1983). From Parseval’s theorem,

\[ \sum_{k=0}^{N-1} |c(k)|^2 = \frac{1}{N} \sum_{j=-N/2}^{N/2-1} \ln_{2} j^2, \]

(A1)

where \( c(k) \) and \( a_j \) are defined in Section 4. The variance of \( c(k) \) is defined as

\[ \sigma^2 = \frac{1}{N} \sum_{k=0}^{N-1} (c(k) - \bar{c})^2 = \bar{c}^2 - \bar{c}^2, \]

(A2)

where \( \bar{c}^2 \) is the mean value of \( c^2 \) and \( \bar{c} \) is the mean value of \( c \). Starting with equation (A2), plugging in from equation (A1), and using the fact that \( a_0 = C_{\text{tot}} \),

\[ \sigma^2 = \frac{1}{N^2} \sum_{j=-N/2}^{N/2-1} |\ln_{2} j|^2 - \frac{1}{N^2} \sum_{j=-N/2}^{N/2-1} a_j^2 \]  

(A3)

\[ \sigma^2 = \frac{1}{N^2} \sum_{j=-N/2}^{N/2-1} |\ln_{2} j|^2. \]  

(A4)

\[ \sigma^2 = \frac{1}{N^2} \sum_{j=-N/2}^{N/2-1} a_j^2. \]  

(A5)

Using the Leahy et al. normalization (equation 18), one can then write

\[ \sigma^2 = \frac{1}{N} \sum_{j=-N/2}^{N/2-1} C_{\text{tot}} P_j \]  

(A6)

\[ \sigma^2 = \frac{C_{\text{tot}}}{N^2} \left( \sum_{j=-N/2}^{N/2-1} P_j + \frac{1}{2} P_{N/2} \right), \]  

(A7)

where in the last step we used the fact that \( |ln_j| = ln_{-j} \). The fractional rms variation squared is then

\[ s^2 = \sigma^2 \frac{N^2}{C_{\text{tot}}} = \frac{1}{C_{\text{tot}}} \left( \sum_{j=1}^{N/2-1} P_j + \frac{1}{2} P_{N/2} \right). \]  

(A8)

As an example, we examine a light curve with variations due to Poisson statistics only. For such a light curve, we expect \( \sigma^2 = \bar{c}^2 \) and therefore \( s^2 = 1/\bar{c} = N/C_{\text{tot}} \). Setting the expression for \( s^2 \) in equation (A8) equal to \( s^2 = 1/\bar{c} = N/C_{\text{tot}} \) for Poisson noise, we
find
\[ \frac{N}{C_{\text{tot}}} = \frac{1}{C_{\text{tot}}} \left( \sum_{j=1}^{N/2-1} p_j p_j + \frac{1}{2} P_{N/2} \right), \] (A9)

or
\[ \frac{2}{N} \left( \sum_{j=1}^{N/2-1} p_j p_j + \frac{1}{2} P_{N/2} \right) = 2 \] (A10)

\[ \Rightarrow P = 2 + \frac{P_{N/2}}{N} \approx 2. \]

where \( P \) is the average power excluding the D.C. power \( P_0 \). So, for the power spectrum of Poisson noise with the Leahy normalization, the mean value of the power at non-zero frequencies is approximately 2, and the fractional variation, \( s^2 \), is inversely proportional to the mean count rate.