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DISCOVERY OF A MAGNETIC WHITE DWARF IN THE SYMBIOTIC BINARY Z ANDROMEDAE

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ABSTRACT

We report the first result from our survey of rapid variability in symbiotic binaries: the discovery of a persistent oscillation at $P = 1682.6 \pm 0.6$ s in the optical emission from the prototype symbiotic Z Andromedae. The oscillation was detected on all eight occasions on which the source was observed over a time span of nearly 1 yr, making it the first such persistent periodic pulse found in a symbiotic binary. The amplitude was typically 2–5 mmag, and it was correlated with the optical brightness during a relatively small outburst of the system. The most natural explanation is that the oscillation arises from the rotation of an accreting magnetic ($B_S \gtrsim 10^5 G$) white dwarf. This discovery constrains the outburst mechanisms, since the oscillation emission region near the surface of the white dwarf was visible during the outburst.

Subject headings: accretion, accretion disks — binaries: symbiotic —
stars: individual (Z Andromedae) — stars: magnetic fields — stars: oscillations —
stars: rotation

1. INTRODUCTION

When the term “symbiotic star” was coined in the early 1940s for the newly discovered peculiar variable stars with combination optical spectra (see Kenyon 1986), Z Andromedae was one of the prototypes. Today, it remains one of the most frequently observed symbiotic systems (SS). The observations have revealed a complex system that is still not fully understood (Mikołajewska & Kenyon 1996). Most evidence indicates that the hot star in Z And is a white dwarf (WD), and the work we present here supports that conclusion. This evidence includes effective temperature estimates of the hot component of approximately 10^5 K (Fernández-Castro et al. 1988; Murset et al. 1991), an inferred hot component radius of approximately 0.07 $R_\odot$ (Fernández-Castro et al. 1988; Murset et al. 1991), and a large radio nebula (Seaquist, Taylor, & Button 1984), which is not expected if mass transfer occurs via Roche lobe overflow onto a main-sequence star. The binary has an orbital period of 759 days (Formiggini & Leibowitz 1994; Mikołajewska & Kenyon 1996), and Schmid & Schild (1997) have used Raman line polarimetry to determine an orbital inclination of $i \approx 47^\circ \pm 12^\circ$ and infer a mass for the hot component of 0.65 ± 0.28 $M_\odot$ (assuming a total system mass between 1.3 and 2.3 $M_\odot$).

According to current theories of binary evolution (Yungelson et al. 1995), most WDs found in symbiotics should have evolved from stars with main-sequence masses greater than about 1.5 $M_\odot$. Highly magnetic WDs ($B_S \gtrsim 10^6 G$, where B_S is the field at the stellar surface) appear to be preferentially formed by stars with main-sequence masses $M \approx 2$–4 $M_\odot$ (Angel, Borra, & Landstreet 1981; Sion et al. 1988), and so it is possible that the fraction of WDs that are magnetic is higher in symbiotics than in the field, where it is about 3%–5% (Chanmugam 1992). Given that there are at least 150 known SS, and that most of these contain WDs, we expect some SS to contain WDs that are magnetized at the level seen in DQ Her and AM Her cataclysmic variables ($B_S \gtrsim 10^5 G$).

Mikołajewski, Mikołajewski, & Khudyakova (1990a), Mikołajewski et al. (1990b), and also Mikołajewski & Mikołajewska (1988), have invoked the presence of a magnetic WD to explain the jets, flickering with possible QPOs, and large changes in the hot component luminosity in the symbiotic star CH Cyg, and this idea was also later adopted in the case of another symbiotic, MWC 560 (Tomov et al. 1992; Michalitsianos et al. 1993). However, stable and repeatable oscillations like those detected in magnetic cataclysmic variables have until now not been seen in a symbiotic, and the prevalence of magnetic WDs in SS is an important unknown.

We are undertaking a long-term observational program to study the minute timescale photometric behavior of symbiotic binaries, expanding on the work of Dobrzycka, Kenyon, & Milone (1996) and others. In § 2, we present the first result from our survey, the discovery of a 28 minute oscillation in the *B*-band emission from Z And. This was the only strong oscillation found in the preliminary analysis of 20 objects. Results from the complete survey will be presented in a future paper. In § 3, we interpret this oscillation as due to accretion onto a magnetic, rotating WD. The fact that the oscillation was detected during a recent outburst, as well as once the source had returned to quiescence, has implications for outburst models, as we outline in our conclusions (§ 4).

2. OBSERVATIONS AND RESULTS

We observed Z And on seven occasions separated by 2–4 weeks each from 1997 July to 1997 December, and then once again in 1998 June, with the 1 m Nickel telescope at UCO/Lick Observatory. The observations ranged in length from approximately 4 hr on a single night in 1997 July to approximately 7 hr night^{-1} three nights in a row in 1997 November, for a total of 76 hr of observing on 13 nights spanning 1 yr (see Table 1). The 2048 × 2048 pixel, 6'.3 × 6'.3, unthinned LORAL CCD currently in Lick's Dewar 2 and a Johnson B filter were always used. The first observation fortuitously occurred about 1 month after the peak

TABLE 1

Observation Log and Results

Observation Number	Date (UT)	MJD ($-2{,}450{,}000$)	Orbital Phase[a]	Observation Length (hr)	$t_{\rm exp}$ (s)	Δt (s)	Count Rate ($\times 10^4 c$ s^{-1})	Oscillation Period (s)
1	1997 Jul 8	637	0.50	3.7	18	40	2.9	1676 ± 19
2	1997 Aug 2	663	0.54	6.0	30	58	2.3	1686 ± 11
3	1997 Aug 30	691	0.58	6.5	30	57	1.9	1695 ± 15
4	1997 Sep 13	705	0.59	8.0	38	63	1.9	1682.2 ± 0.7
	1997 Sep 14	706	0.60	5.1	65	90		
5	1997 Oct 5	727	0.62	6.5	50	78	1.6	1684.2 ± 1.5
	1997 Oct 6	728	0.62	6.2	52	79		
6	1997 Nov 1	754	0.66	6.2	40	68	1.4	1682.7 ± 1.0
	1997 Nov 2	755	0.66	7.7	65	93		
	1997 Nov 3	756	0.66	7.1	40	68		
7	1997 Dec 2	785	0.70	5.8	110	138	1.2	1679 ± 16
8	1998 Jun 28	993	0.97	3.4	200	228	0.5	1682.0 ± 3
	1998 Jun 29	994	0.98	3.7	200	228		

Note.—$t_{\rm exp}$ is the integration time, and Δt is the time between integration starts, which is equal to the integration time plus the CCD readout and processing time.

[a] From the Formiggini & Leibowitz 1994 ephemeris: Min(vis) = JD 2,442,666(± 10) + 758.8(± 2)E, where E is the number of orbital cycles.

of an optical outburst ($\Delta V \approx 1$), and the subsequent observations in 1997 took place as the optical flux declined. At the time of the 1998 June observation, the optical flux had returned to its preoutburst quiescent value. A 2.2 yr V-band light curve is shown in Figure 1, with the times of our observations marked.

At the time of the first observation, on 1997 July 8, the binary was oriented with the WD in front of the red giant from the observer's perspective (i.e., the orbital phase of the binary was 0.5, where phase 0.0 corresponds to photometric minimum in quiescence and spectroscopic conjunction). By 1997 December 2, the binary had moved through almost one quarter of its orbit to phase 0.7, where both stars are roughly equidistant from the observer, and in 1998 June, the WD was behind the red giant.

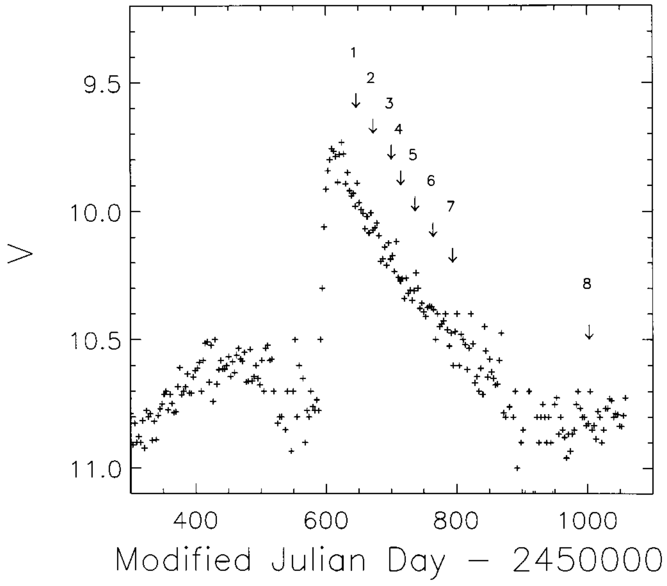

Fig. 1.—Long-term V-band light curve of Z And, from the American Association of Variable Star Observers (J. A. Mattei 1998, private communication). The times of our eight observations are marked with arrows; see Table 1 for the corresponding dates.

Data reduction was performed using IDL software based on standard IRAF routines. Source counts for each image were extracted from a circular aperture with a radius of 8″–14″, and the background was estimated from a surrounding annulus. For each light curve, the extraction region was chosen to be much larger than the seeing, so that any variability due to source counts falling outside the extraction region (as the seeing or guiding quality changed) was small compared to systematic errors. Z And is bright enough that even with large extraction regions, the Poisson errors from sky background are usually not significant. Several representative light curves from our observations are shown, in chronological order, in Figure 2. There is one other bright star in the field of Z And (at J2000 coordinates $23^{\rm h}33^{\rm m}24^{\rm s}.0$, $+48'45''38''.0$), but it is also variable, so it was not used as a comparison star for differential photometry (except for one night in October when its amplitude of variability was low, and one night in November when thick clouds were present). Therefore, although every attempt was made to perform observations on clear nights, some observations were affected by high clouds. Data points affected by radiation events ("cosmic rays") were removed when they could be identified, and the light curves were corrected for atmospheric extinction. In addition, we divided most of the light curves by a third-order polynomial in order to remove residual atmospheric effects ($\lesssim 1\%$ effect). Note that this may have also removed any intrinsic variability on a timescale comparable to the length of the observation. This polynomial fitting was not performed for the 1997 August 2 and August 30 data because of the presence of flarelike variability in the light curves (see Fig. 2).

Power spectra corresponding to the light curves in Figure 2 are shown in Figure 3. The most striking persistent feature is the peak at 0.6 mHz, corresponding to a period of 28 minutes. A smaller but still significant peak is also present at twice this frequency in the power spectra of the 1997 July 8 (not shown), August 2, August 30, and September 13 light curves. The 28 minute oscillation was significantly detected in all eight observations. The power spectrum of the other bright star in the field does not show the feature at 0.6 mHz,

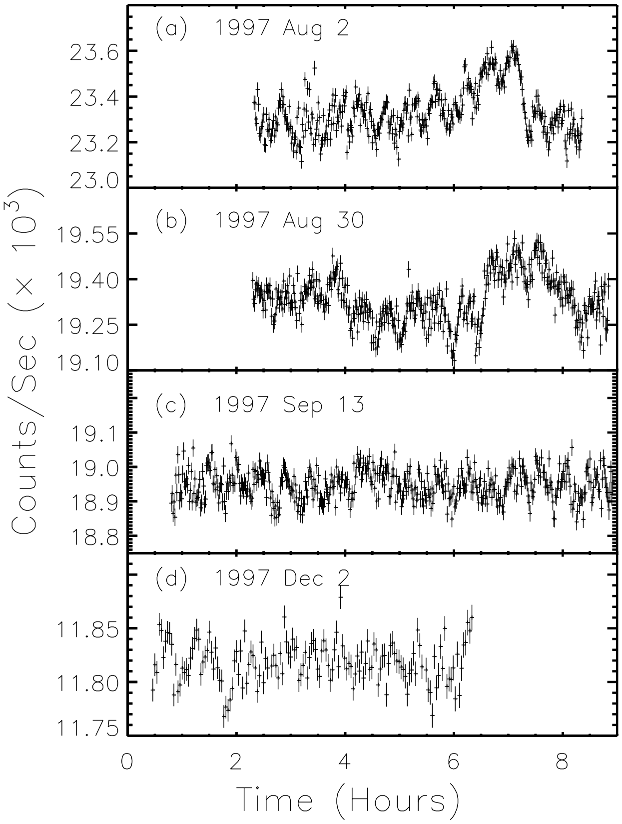

FIG. 2.—Four *B*-band light curves of Z And. The light curves have been corrected for atmospheric extinction and normalized to a typical value of the count rate. The 28 minute oscillation is clearly visible in at least three of the four light curves. The additional variability on 1997 August 2 and August 30 could be intrinsic to Z And, but the lack of a constant comparison star prohibits us from ruling out atmospheric origins.

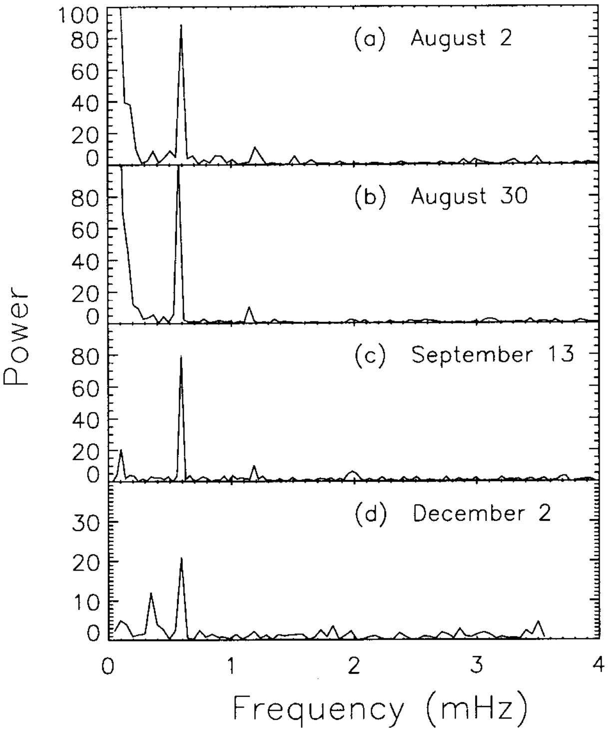

FIG. 3.—Power spectra for the light curves in Fig. 2. The power is plotted in units of mean high frequency power (which is "white"), and the feature at 0.6 mHz corresponds to an oscillation period of 28 minutes. A smaller feature at 1.2 mHz is also seen (and significantly detected) in the top three panels. The features at frequencies lower than 0.6 mHz are not repeated from one observation to another, and could be due to atmospheric changes or source variability.

confirming that the oscillation detected in Z And was neither instrumental nor atmospheric in origin.

2.1. *Timing Analysis*

Although the feature at 0.6 mHz is detected in the power spectra of Z And, the precise value of the oscillation period and its uncertainty is best determined in the time domain. Visual inspection of the light curves suggests that the signal is not a simple sinusoid, and the detection of a harmonic in several of the power spectra confirms this impression. By using time domain epoch folding techniques, we need not make any assumptions about the shape of the pulse profile, and all of the signal "power" will be located at a single period.

To perform this analysis, we used the phase dispersion minimization (PDM) technique originally described by Stellingwerf (1978). The PDM technique consists of folding a light curve at a range of periods and computing the mean pulse profile, and the scatter of the data points about this profile, for each period. Each data point is assigned a phase $\phi = t \bmod P$, where t is the time of the measurement from some initial time and P is the fold period, and binned accordingly. In our case the number of phase bins ranged from 10 to 20 and was chosen to be as large as possible while still ensuring that each phase bin contained enough data for our statistics to be valid (at least 10 data points). With a large number of points in each bin, the standard PDM statistic is just χ^2,

$$\chi^2 = \sum_{i=1}^{n_b} \sum_{j=1}^{n_i} \frac{(x_{ij} - m_i)^2}{\sigma_{ij}^2} , \tag{1}$$

where n_b is the number of phase bins, n_i is the number of points in bin i, x_{ij} is the jth point in the ith phase bin, $m_i = n_i^{-1} \sum x_{ij}$ is the mean of all points in bin i, and σ_{ij} is the uncertainty on x_{ij}. In our treatment, the σ_{ij} were usually dominated by the Poisson errors on the source counts. The mean pulse profile will be rather flat for fold periods far from the true period, and the points in each phase bin will have a large variance, causing χ^2 to be large. For a fold period close to the true period, the mean profile will approach the true pulse profile, the variance of the points in each bin will be small, and χ^2 will decrease. The best estimate of the true period is found by minimizing χ^2.

For a data stream with Gaussian noise and a superimposed oscillation, $\chi^2_{\rm min}$, the minimum value of χ^2, should be approximately equal to the number of degrees of freedom (in this case $N - n_b$, where N is the total number of points). In other words, the reduced χ^2 is approximately equal to 1, indicating that the fit of the data to the mean profile is good. If the errors are normally distributed, there is also a simple relationship between $\Delta\chi^2$ above the minimum and the level of confidence that the true period lies within the range that produce $\chi^2 \leq (\chi^2_{\rm min} + \Delta\chi^2)$. For models with only one free parameter, like ours, $\Delta\chi^2 = 1$ corresponds to a 68.3% confidence level, and $\Delta\chi^2 = 2.71$ corresponds to a 90% confidence level. If underlying red noise is present at the period

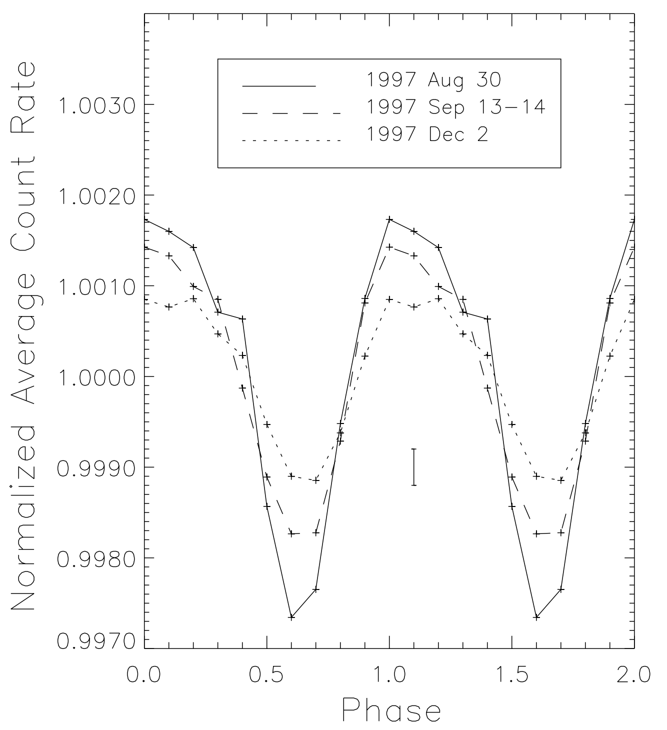

FIG. 4.—Z And pulse profiles at $P = 1683$ s from 1997 July 7, 1997 August 30, and 1998 June 28–29. Error bars are left off for clarity of viewing, but 1 σ is about 0.0003 in the normalized units plotted, as shown by the mark in the center of the plot. The data are repeated for clarity. The decrease in pulse amplitude for later observations is significant.

of interest, the task of identifying an oscillation and measuring its parameters is much more difficult. Very long baselines or repeated observations are then needed to characterize the underlying variability. For Z And, any red noise is at longer periods than the detected oscillation, so we did not have this added complication.

For data with noise properties that are not precisely Gaussian, the PDM technique can still be used with the help of simulations to determine the correct relationship between $\Delta\chi^2$ above the minimum and confidence levels (M. van der Klis 1998, private communication; Press et al. 1992). We performed such simulations for each light curve by repeatedly injecting a fake signal with a known period into the data, and then examining the distribution of periods resulting from the PDM method.

The period of the oscillation as determined from each observation individually is shown in the last column of Table 1, where the quoted errors are roughly 68% confidence limits. The measurements from observations with more than one night of observing are more precise than single night observations because of the longer baseline. The period measurements from all observations are consistent, which indicates that the period was stable to within less than 15 s, or 1% of the period, for 1 yr and during an outburst of the system. More accurate determination of the oscillation period in Z And by connecting the data from adjacent observations will allow for important orbital time delay measurements. Given the system inclination of $i = 47°$ and taking the total system mass to be $M_{\rm tot} = 2\ M_\odot$, which is typical for a symbiotic (Schmid & Schild 1997, and references therein), the light travel time across the WD orbit is $(a_{\rm WD} \sin i)/c \approx 12.2$ minutes $(\sin i/0.73)(M_{\rm tot}/2\ M_\odot)^{1/3}(1 + M_{\rm WD}/M_{\rm RG})^{-1}$, where $a_{\rm WD}$ is the distance from the WD to the center of mass, $M_{\rm WD}$ is the mass of the WD, and $M_{\rm RG}$ is the mass of the red giant.

The peaks at twice the fundamental frequency in the early data indicate that the pulse profile deviates from a sinusoid. Pulse profiles created by folding the light curves from observations 3, 4, and 7 at 1683 s are shown in Figure 4. The pulse fraction decreased monotonically as the outburst decayed, from ≈ 5 mmag peak-to-peak in 1997 July and August (observations 1–3) to ≈ 2 mmag peak-to-peak in 1997 December (observation 7). In 1998 June the oscillation was detected at the 2 mmag level.

3. THE CASE FOR MAGNETIC ACCRETION

We interpret the 28 minute oscillation as the result of rotation of a WD that has a strong enough magnetic field to channel the accretion flow onto its magnetic polar caps, as in the DQ Her systems (Patterson 1994). Nonradial g-mode pulsations of a hot WD that is similar to a planetary nebula nucleus (PNN) is another plausible explanation of the oscillation, especially since g-mode pulsations with periods close to 28 minutes have been observed in several PNN (Ciardullo & Bond 1996). However, these systems are multiperiodic and have frequencies that change on month-long timescales. The Z And emission oscillated at only a single, constant frequency for an entire year, as well as throughout an outburst during which conditions in the WD envelope presumably changed significantly. Therefore, we conclude that WD g-mode pulsations are unlikely to be the cause of the oscillation. The period of the oscillation is too long to be due to an acoustic (p-mode) pulsation in a WD, and too short to be due to a g-mode pulsation in a main-sequence star with $M \approx 0.65\ M_\odot$. A p-mode pulsation in a main-sequence star is not formally ruled out, but again one would expect more than a single mode to be present. Therefore, the period, its stability and coherence, and the fact that only one period is detected all support the WD magnetic dipole rotator model.

The minimum magnetic field strength at the dipolar cap, B_S, that is needed to funnel the accretion onto the star can be roughly estimated by requiring that the magnetospheric radius, $r_{\rm mag}$, be larger than the WD radius, R. At the magnetospheric radius, the magnetic field pressure is comparable to the ram pressure of the in-falling material, giving the standard $r_{\rm mag} \approx (\mu^4/2GM_{\rm WD}\dot{M}^2)^{1/7}$, where $\mu = B_S R^3/2$ is the magnetic dipole. This then leads to a minimum field

$$B_S \gtrsim 3 \times 10^4 G \left(\frac{10^9\ {\rm cm}}{R}\right)^{5/4} \left(\frac{\dot{M}}{10^{-8}\ M_\odot\ {\rm yr}^{-1}}\right)^{1/2} \times \left(\frac{M_{\rm WD}}{0.65\ M_\odot}\right)^{1/4} . \qquad (2)$$

If the WD has been spun up so that it is in a rotational equilibrium, with its spin period P_s equal to the Kepler period at $r_{\rm mag}$, then the magnetospheric radius would be

$$r_{\rm mag} \approx \left(\frac{GM_{\rm WD} P_s^2}{4\pi^2}\right)^{1/3} \approx 0.26\ R_\odot \left(\frac{M_{\rm WD}}{0.65\ M_\odot}\right)^{1/3} \left(\frac{P_s}{28\ {\rm min}}\right)^{2/3} , \qquad (3)$$

and the field strength needed to have the magnetosphere at this radius is roughly

$$B_S \approx 6 \times 10^6 G \left(\frac{\dot{M}}{10^{-8}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{1/2} \left(\frac{10^9\ \mathrm{cm}}{R}\right)^3 \times \left(\frac{M_{\mathrm{WD}}}{0.65\ M_\odot}\right)^{5/6} . \quad (4)$$

The time it takes for the WD to reach this rotational equilibrium is $t_{\text{spin-up}} = 2\pi I/NP_s \approx 5 \times 10^4$ yr (28 minutes/P_s)(10^{-8} $M_\odot$ yr$^{-1}/\dot{M}$), where $I \approx M_{\mathrm{WD}} R^2/5$ is the WD moment of inertia, and $N = \dot{M}(GM_{\mathrm{WD}} r_{\mathrm{mag}})^{1/2}$ is the accretion torque. This spin-up time is shorter than the lifetime of the red giant, so it is likely that the system has reached this form of equilibrium.

4. CONCLUSIONS AND IMPLICATIONS FOR THE OUTBURST MECHANISM

Our survey has so far yielded one persistent periodic oscillator. The oscillation was detected on all eight occasions when the source was observed over the course of 1 yr, and the period, $P = 1682.6 \pm 0.6$ s, was stable to within our measurement errors. We interpret this oscillation in terms of magnetic accretion onto a rotating WD. This detection is the first of its kind for a symbiotic, and it comes from an object, Z And, in which no other phenomena thought to be associated with magnetism have been observed. Outburst mechanisms need to be reconsidered in light of this discovery, and as we now elaborate, accretion disk instabilities look to be a promising source for the outbursts.

The detection of an oscillation that originates at the WD surface during an outburst has serious consequences for models of the outburst mechanism in Z And. Most models (Mikołajewska & Kenyon 1992, and references therein) invoke dramatic expansion of the WD photosphere, for example, as the result of a thermonuclear shell flash or a change in $\dot{M}$ onto a nearly stably burning hydrogen layer. Evidence for such expansion and the subsequent decrease in the effective temperature of the WD includes a decrease in the strength of high ionization state emission lines, line broadening, increased opacity as measured by line ratios, the appearance of an A-F–type spectrum, and direct luminosity estimates, all during outburst (Fernández-Castro et al. 1995; Mikołajewska & Kenyon 1996). Mikołajewska & Kenyon (1996) deduced that the radius of the hot component increased by a factor of ∼100 during previous outbursts of Z And. However, they also noted a few problems with the shell flash/photospheric expansion model. The He II emission lines evolve in a different manner than other emission lines during outbursts. Therefore, the outburst spectra are inconsistent with an evolving single temperature model for the WD.

Another problem for thermonuclear runaway and steady burning shell expansion models is the timescales. It is difficult to reconcile theoretical photospheric expansion timescales and shell flash recurrence timescales with the observations (Mikołajewska & Kenyon 1992, and references therein), especially for a low-mass WD (although see Sion & Ready 1992). Our detection of an oscillation from a region that would be hidden by an expanded photosphere is another phenomenon that is difficult to reconcile with models involving photospheric expansion.

Our observations do not provide information about the temperature evolution of the hot component, so it is possible that the 1997 outburst was significantly different from previous outbursts. The 1997 outburst was smaller and more asymmetric than either of two well-studied outbursts in 1984 and 1986, which rose to $V \approx 9.6$ and $V \approx 9.1$, respectively, compared to $V \approx 9.7$ for the 1997 outburst. Based on multiwavelength observations, Fernández-Castro et al. (1995) suggested that the 1984 and 1986 events were similar, but that a less massive shell was ejected during the 1984 outburst. The 1984 event produced a smaller increase in opacity (Fernández-Castro et al. 1995), so a correlation between V at the outburst peak and the nature of the outburst might exist.

Another outburst mechanism that has been discussed for SS, although usually not for systems that contain WDs, is thermal accretion disk instabilities (DI; Duschl 1986a, 1986b) like those that lead to dwarf novae eruptions in cataclysmic variables (Osaki 1996). DI models have not been considered prime candidates for explaining the outbursts in WD SS for several reasons. First of all, there is little direct evidence for disks around WDs in SS. Disks are not needed in spectral fits (Murset et al. 1991), and double-peaked line profiles cannot be definitively linked to disk emission (Robinson et al. 1994). Furthermore, disk instabilities alone may not provide sufficient energy to explain the observed flux increases (Kenyon 1986). DI models can, however, produce timescales that are more in accordance with the durations and recurrence times seen in SS outbursts than thermonuclear runaway models. We will explore more fully in a separate paper the possibility that disk instabilities play an important role in SS outbursts.

There are several points that are important to note here, however. Most importantly, if a large disk does exist around the WD in Z And, it could be thermally unstable (Duschl 1986b; Meyer-Hofmeister 1992). Second, during a DI-induced outburst, the emission region close to the WD could remain exposed, as appears to be the case during the most recent outburst of Z And. Finally, the presence of a quasi-steady burning layer on the WD may affect the energetics of the outburst resulting from a DI.

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