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CH CYGNI. II. OPTICAL FLICKERING FROM AN UNSTABLE DISK

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ABSTRACT

CH Cygni began producing rapid, stochastic optical variations with the onset of symbiotic activity in 1963. We use changes in this flickering between 1997 and 2000 to diagnose the state of the accretion disk during this time. In the 1998 high state, the luminosity of the *B*-band flickering component was typically more than 20 times higher than in the 1997 and 2000 low states. Therefore, the physical process or region that produces the flickering was also primarily responsible for the large optical flux increase in the 1998 high state. Assuming that the rapid, stochastic optical variations in CH Cygni come from the accretion disk, as in cataclysmic variable stars, a change in the accretion rate through the disk led to the 1998 bright state. All flickering disappeared in 1999, when the accreting white dwarf was eclipsed by the red giant orbiting with a period of approximately 14 yr, according to the ephemeris of Hinkle et al. and the interpretation of Eyres et al. We did not find any evidence for periodic or quasi-periodic oscillations in the optical emission from CH Cygni in either the high or low state, and we discuss the implications for magnetic propeller models of this system. As one alternative to propeller models, we propose that the activity in CH Cygni is driven by accretion through a disk with a thermal-viscous instability similar to the instabilities believed to exist in dwarf novae and suggested for FU Ori pre–main-sequence stars and soft X-ray transients.

Subject headings: accretion, accretion disks — binaries: eclipsing — binaries: symbiotic — instabilities — techniques: photometric

1. INTRODUCTION

Observationally, the symbiotic star CH Cygni is a very complex system (see Kenyon 2001 for a review of its properties). It contains an accreting white dwarf (WD) fed from the wind of a red giant and surrounded by an ionized nebula. There is much debate over whether CH Cygni is a double or a triple system. It displays at least three or four long-period photometric or radial velocity variations (~100 days for the red giant pulsation, ~760 days from either an inner binary orbit or repetition of short *U*-band activity dropouts and radial velocity variations, 5200–5700 days for the binary orbit, or outer stellar orbit, and a possible 32 yr *JHK* variation). In addition to collimated jets, the hot component also produces a less collimated outflow during periods of activity (Eyres et al. 2002; Skopal et al. 2002). Episodes of dust condensation further complicate analysis of the stellar components.

In the face of this complexity, one way to isolate emission from the accretion region is to examine rapid (timescales of minutes to hours) optical variations. It is very unlikely that the red giant in CH Cygni could produce variations on a timescale of minutes or seconds, given a dynamical time $t_{\rm dyn} \sim (R^3/GM)^{1/2}$, which is generally greater than 0.5 days. In fact, high time resolution *U*-band photometry of CH Cygni by many authors (e.g., Mikołajewski et al. 1990b and references therein) indicates that the rapid variations come from the hot component and not the red giant. In another symbiotic star, T CrB, Zamanov & Bruch (1998) found flickering "indistinguishable" from that seen in cataclysmic variables (CVs), and they concluded that it is therefore probably also produced in the vicinity of the WD.

In this paper, we investigate the role of the accretion disk in optical brightness state changes in CH Cygni. We performed rapid optical photometry and optical spectroscopy for CH Cygni between 1997 and 2000. Our observations cover several interesting phases. In 1997 CH Cygni produced a radio jet after a drop in the optical flux (Karovska, Carilli, & Mattei 1998; observations from this period are discussed in Sokoloski & Kenyon 2003, hereafter Paper I). In 1998 it entered a high activity state; in 1999 the hot source was eclipsed by the red giant (according to Eyres et al. 2002). The properties of the optical flickering changed during each of these phases, and in combination with the optical spectra, these changes provide information about the accretion disk during jet production, the nature of the high activity state, and the timing of the eclipse.

This paper is divided into six sections. After the initial description of the observations in § 2, we report the results from our fast photometry in § 3. In § 4 we discuss the disappearance of all minute-to-hour timescale variations during the proposed eclipse of the accreting WD by the red giant in 1999. In § 5 we describe the timing analysis of the light curves. No coherent or quasi-periodic oscillations were found, and we discuss the difficulty for magnetic propeller models of CH Cygni in the face of this lack of evidence for a strong magnetic field. In § 6 we suggest that the activity in CH Cygni may instead be driven by an unstable accretion disk.

2. OBSERVATIONS AND DATA ANALYSIS

We performed high time resolution optical differential photometry at *B* and at *U*, using the 1 m Nickel telescope at Lick Observatory, on 14 nights between 1997 and 2000 (see Sokoloski, Bildsten, & Ho 2001 for description of observing technique and instruments). Eclipses in the best comparison star, SAO 31628 (see Sokoloski & Stone 2000), affected three of the 14 observations. To obtain a uniform, high-quality set of light curves with this comparison star, we divided its light curves on 1998 July 22 and 2000 June 22 by a sixth-order polynomial fit to the eclipse profile. This correction added only a small amount of power to the power spectrum of the CH Cygni observations, as measured by computing the power spectrum of the ratio of SAO 31628 and a second comparison star in the field. This slight extra power only appeared at the lowest frequencies and did not hamper our search for coherent oscillations. It also did not diminish our ability to measure the power-law slope on 1998 July 22 since it was insignificant compared to the actual broadband power due to intrinsic variations from CH Cygni. On 1999 July 3, the SAO 31628 eclipse only affected the last 80 minutes of a 6 hr light curve, so the affected portion of the data was not used. Table 1 lists the photometric observations.

P. Berlind, M. Calkins, and several other observers acquired low-resolution optical spectra of CH Cygni with FAST, a high throughput, slit spectrograph mounted at the Fred L. Whipple Observatory 1.5 m telescope on Mount Hopkins, Arizona (Fabricant et al. 1998). They used a 300 groove mm^{-1} grating blazed at 4750 Å, a 3″ slit, and a thinned Loral 512 × 2688 CCD. These spectra cover 3800–7500 Å at a resolution of 6 Å. We wavelength-calibrated the spectra in NOAO IRAF.[1] After trimming the CCD frames at each end of the slit, we corrected for the bias level, flat-fielded each frame, applied an illumination correction, and derived a full wavelength solution from calibration lamps acquired immediately after each exposure. The wavelength solution for each frame has a probable error of ±0.5 Å or better. To construct final one-dimensional spectra, we extracted object and sky spectra using the optimal extraction algorithm APEXTRACT within IRAF. Most of the resulting spectra have moderate signal-to-noise, $S/N \gtrsim 30$ pixel^{-1}.

3. PHOTOMETRIC RESULTS

Our high time resolution light curves demonstrate tremendous diversity in both amplitude and frequency content (see Fig. 1). The observations from 1997 show low-amplitude ($\Delta m < 0.15$ mag) variations that initially are unusually smooth. The evolution of the light curve in 1997, when a radio jet was produced, is discussed in Paper I. In 1998 July and August, we see full, large-amplitude ($\Delta m \sim 0.5$ mag) CV-like flickering when CH Cygni is in a high state. Figure 2 shows the four high-state light curves from 1998. In 1999 July, the optical flux is constant to the level of a few tenths of a percent. Finally, in 2000 June and July, we again see low-amplitude flickering after CH Cygni returns to an optical low state. The optical brightness levels we refer to as "high," "low," and "very low" are marked on the long-term AAVSO light curve shown in Figure 3. Figure 4 shows examples of power spectra from the low-state, high-state, and eclipse light curves (excluding the unusual light curves from early 1997, which are discussed in Paper I). The power spectra were generally well fitted with power-law plus a constant (for the high-frequency white noise) models, $P = Af^{-\alpha} + B$, with power-law index $\alpha = 1.8 \pm 0.1$. In the 2000 low state, the power law was slightly flatter, with $\alpha \approx 1.6$ on 2000 June 22 and $\alpha \approx 1.3$ on 2000 July 3.

Table 2 lists two measures of the overall variability amplitude for each observation (except observation 10 on 1999 July 14, for which the weather was poor). The fractional rms variation (in mmag) is in column (2). Column (3) lists the fractional variation multiplied by the approximate B-band luminosity of CH Cygni at the relevant epoch (taking a bandwidth of 1000 Å) to provide an estimate of the optical luminosity of the variable component, $L_{B,\rm var}$.

4. DISAPPEARANCE OF FLICKERING DURING THE LONG-PERIOD ECLIPSE

There has been much debate over whether CH Cygni is a double or a triple stellar system (e.g., in favor of triple:

TABLE 1
LOG OF PHOTOMETRIC OBSERVATIONS

Observation	Date (UT)	Observation Start (MJD)	Observation Length (hr)	$t_{\rm exp}/\Delta t$ (s)[a]	Number of Points	Filter
1....................	1997 Apr 5	50,543.415	2.9	40.0/58.520	170	B
2....................	1997 Jun 9	50,608.240	3.3	20.0/37.707	313	B
	1997 Jun 9	50,608.392	2.4	13.0/31.377	276	B
3....................	1997 Aug 5	50,665.196	7.3	10.0/32.0	819	B
4....................	1998 Jul 19	51,013.383	3.0	7.0/28.0	382	B
5....................	1998 Jul 20	51,014.382	0.7	4.0/27.0	100	B
	1998 Jul 20	51,014.414	2.3	7.0/30.0	279	B
6....................	1998 Jul 22	51,016.391	2.9	7.0/29.0	359	B
7....................	1998 Aug 19	51,044.210	1.5	15.0/35.987	153	U
	1998 Aug 19	51,044.280	4.4	12.0/33.0	477	B
8....................	1999 Jun 12	51,341.205	2.0	20.0/39.100	176	B
9....................	1999 Jun 13	51,342.221	1.8	20.0/39.374	155	B
10..................	1999 Jul 14	51,373.434	1.7	9.0/28.371	150	B
11..................	1999 Jul 15	51,374.431	1.7	9.0/28.347	223	B
12..................	1999 Jul 16	51,375.429	1.7	50.0/68.622	88	B
13..................	2000 Jun 22	51,717.199	7.3	10.0/31.102	843	B
14..................	2000 Jul 3	51,728.233	5.1	30.0/47.555	385	B

[a] Expression Δt is the mean time between observation starts, and it includes the exposure time plus readout and processing.

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[1] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

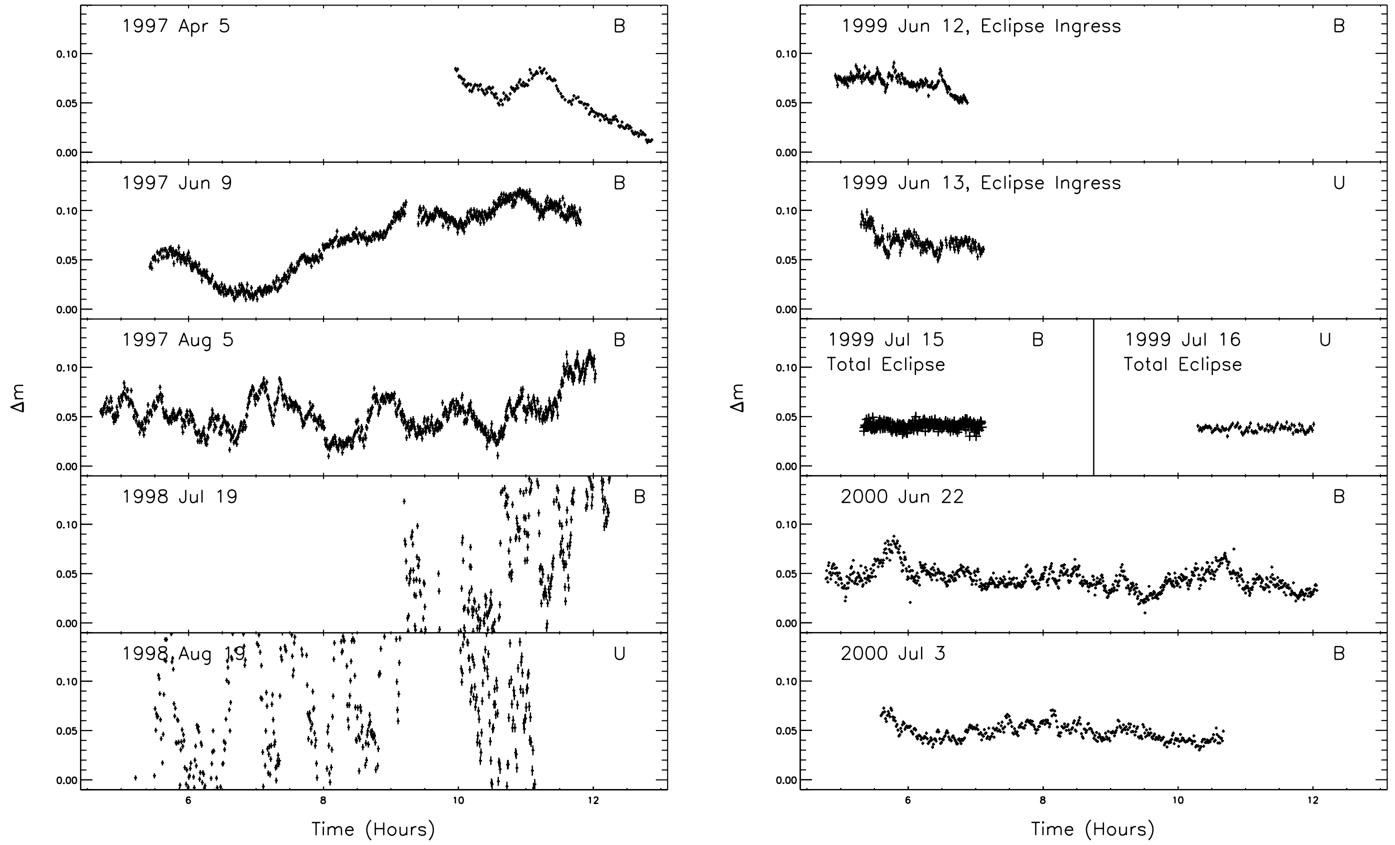

FIG. 1.—Example of CH Cygni light curves from 1997 to 2000. *Left:* Fast photometry, 1997 and 1998. *Right:* Fast photometry, 1999 and 2000. All data are plotted on the same scale for direct comparison (the amplitude of the variations in 1998 span 3 times the magnitude range shown; full high-state light curves are shown in Fig. 2). Low-amplitude flickering is present in 1997 and 2000. All variations disappear during the eclipse of the hot component in 1999.

Hinkle et al. 1993; Skopal 1995; Skopal et al. 1996; Iijima 1998; e.g., in favor of double: Mikołajewska 1994; Munari et al. 1996; Ezuka, Ishida, & Makino 1998). The most controversial contention is that the 756 day radial velocity variations are orbital, in addition to those from the more generally accepted 14 yr orbital period. Our conclusions in this paper do not depend on whether CH Cygni is a double or triple system.

The light curves from our 1999 observations show very little rapid variability. In 1999 June, we see low-amplitude flickering ($\sigma_{\rm rms} < 9$ mmag). The 1999 July light curves are constant at our sensitivity limit of a few millimagnitudes. Our measurement of a very tight flickering upper limit in 1999 July is consistent with both the interpretation by Eyres et al. (2002) of this event as an eclipse by a companion orbiting with a period of roughly 14 yr (and their timing of the eclipse as beginning in early June) and our assumption that the flickering is due to accretion onto the WD. Their evidence for the eclipse includes a deep *U*-band minimum, disappearance of the broad bases of the Balmer emission lines, and the close coincidence of this behavior with spectroscopic conjunction. The eclipse began in early 1999 June, and the minimum of the eclipse occurred at JD $2,451,426 \pm 3$ (Eyres et al. 2002). We detected some variations in 1999 June, when the optical light curve had not quite reached eclipse minimum; the beginning of totality must have fallen between mid-June and mid-July. According to Eyres et al. (2002), the *U*-band flux dropped in about 10 days, beginning in early 1999 June. Some portion of the

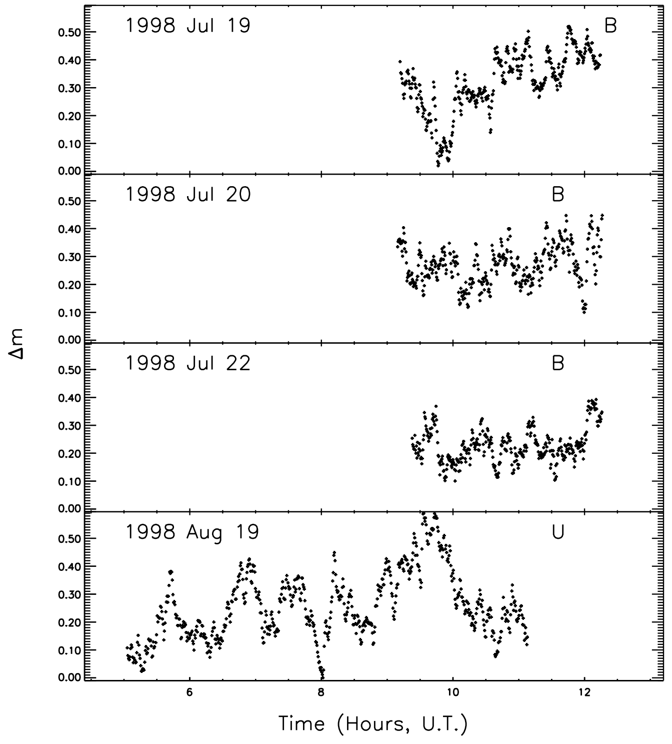

FIG. 2.—Complete set of light curves from the large-amplitude flickering period in 1998, shown full scale. The ordinate for each of these plots spans 0.6 mag (compared to 0.15 mag in Fig. 1).

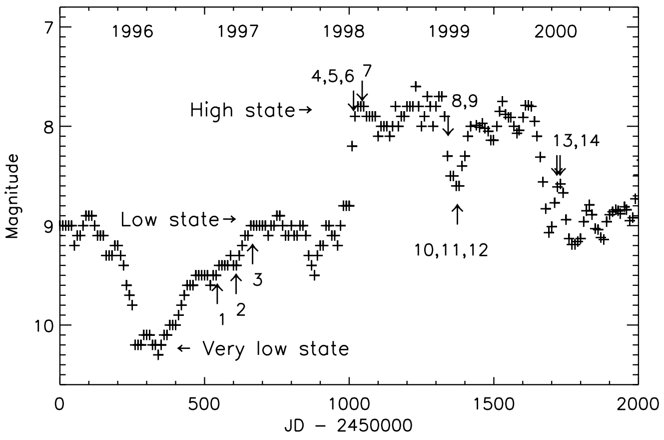

FIG. 3.—Long-term optical light curve of CH Cygni, from the AAVSO. The times of our 14 flickering observations are marked with arrows.

disk may therefore still have been visible on 1999 June 12 and 13.

In Figure 5, a comparison of spectra from before and during the proposed eclipse confirms that the hot component disappeared. During the eclipse, the blue veiling continuum vanished, and the red giant absorption features dominated the spectrum. The He I λ5015 Å emission line from the region close to the WD also disappeared, while the lower excitation Hα, Hβ, and [O III] λ5007 Å emission lines weakened. The lowest excitation [O I] λ6300 emission line, which probably comes from the outermost, low-density region of the nebula, remained unchanged. The overall line changes are consistent with an eclipse of the accreting WD and inner nebula by the red giant.

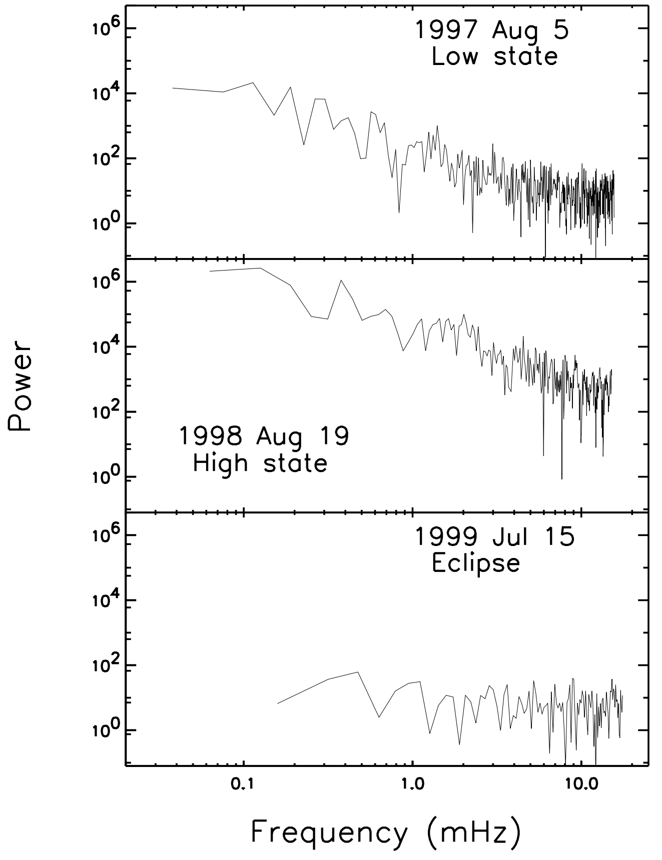

FIG. 4.—Example of power spectra (normalized to the total number of source counts in each observation) from 1997, 1998, and 1999. The power is greater at all frequencies in 1998 August, when the system was in an active state. The bottom panel shows the lack of variations during the WD eclipse.

5. THE QUESTION OF MAGNETISM

Coherent oscillations in optical or X-ray emission are one of the most decisive signatures of magnetic accretion in CVs and X-ray pulsars. Magnetically channeled accretion produces hot spots on the surface of the compact star that rotate in and out of the line of sight at the WD or neutron star spin period. In CVs, X-rays from the rotating accretion column can act like a lighthouse beam illuminating the disk and/or stellar surface. The optical pulsation amplitudes due to magnetic accretion in intermediate polars generally range from a few percent to 10%–20% (Warner 1995). The optical oscillation amplitude for the well-known magnetic propeller AE Aqr is slightly smaller: 0.2%–0.3% when it is quiet, and about 1% during flares (Patterson 1979). Its X-ray emission, however, is modulated with an amplitude of 25% (Warner 1995).

There is currently only one symbiotic binary with convincing evidence for a strongly magnetized WD. Sokoloski & Bildsten (1999) discovered the first symbiotic magnetic accretor in the prototypical symbiotic Z Andromedae. They repeatedly detected a statistically significant oscillation at $P = 1682.6 \pm 0.6$ s, which they interpreted as the spin period of the accreting WD. Thus, coherent brightness oscillations are also a signature of magnetic accretion in symbiotic stars.

To explain the jets and different brightness states in CH Cygni, Mikołajewski & Mikołajewska (1988) proposed a magnetic propeller model based on the oblique rotator theory of Lipunov (1987). They suggested that the inner disk is ejected and a jet produced when the accretion rate onto the WD drops and the system changes from the accretor to the propeller state. In their model, the optical flickering is due to the interaction of the accreted material with a strong magnetic field. Later, Mikołajewski et al. (1990b) reported the detection of an oscillation with a period of 500 s, which they claimed was the rotation period of the WD. If confirmed, this oscillation would provide some support for the magnetic propeller model for CH Cygni (which is discussed further by, e.g., Mikołajewski et al. 1990a, 1990b; Panferov & Mikołajewski 2000).

X-ray, radio, and optical observations by other authors, however, do not support the magnetic interpretation of CH Cygni. Ezuka et al. (1998) observed stochastic X-ray variations on timescales as short as 100 s but did not detect any coherent oscillations. Also, their fit to the X-ray spectrum yielded $kT = 7.3 \pm 0.5$ keV, which they claim is low compared to the $kT = 10$–40 keV typically found for magnetized CVs (Ishida & Fujimoto 1995). By assuming equipartition of energy in the 1986 radio jet, Crocker et al. (2001) estimated a magnetic field strength in the jet that is consistent with a WD surface field strength of only 10 G. In addition, Rodgers et al. (1997) and Hoard (1993) found no evidence of a period between 500 and 600 s in their optical photometry for CH Cygni (although they did claim to find periods at approximately 2200 and 3000 s).

TABLE 2

Amplitude of Stochastic Variations

Observation (1)	Date (UT) (2)	Fractional $\sigma_{\rm rms}$ (mmag) (3)	Approx. $L_{B,\,{\rm var}}$[a] (10^{32} ergs s^{-1}) (4)	Comments (5)
1	1997 Apr 5	20.9	0.6	Low state/disk disrupted?[b]
2	1997 Jun 9	30.7	0.9	Low state/disk disrupted?
3	1997 Aug 5	17.8	0.7	Optical low state
4	1998 Jul 19	106.0	24	Optical high state
5	1998 Jul 20	69.9	17	Optical high state
6	1998 Jul 22	62.6	11	Optical high state
7	1998 Aug 19	119.9	(U)[c]	Optical high state
8	1999 Jun 12	8.8	0.6	Eclipse ingress
9	1999 Jun 13	8.9	(U)	Eclipse ingress
11	1999 Jul 15	3.5	<0.2	Eclipse
12	1999 Jul 16	2.8	(U)	Eclipse
13	2000 Jun 22	11.4	0.7	Optical low state
14	2000 Jul 3	8.2	0.5	Optical low state

[a] Approximate B-band luminosity of the variable component. $L_{B,\,{\rm var}}$ equals the fractional $\sigma_{\rm rms}$, times the relative brightness of CH Cygni compared to SAO 31628, times 8×10^{33} ergs s^{-1} (the approximate luminosity of a $B = 9.62$ mag star at a distance of 268 pc, in a 1000 Å bandwidth).

[b] See Paper I.

[c] U-band measurement only, so no $L_{B,\,{\rm var}}$ estimate available.

To search for oscillations that would indicate magnetic accretion in CH Cygni, we computed power spectra for each of the light curves in our data set. We searched for statistically significant excess power above the broadband red-noise power and found no coherent or quasi-periodic oscillations (see the Appendix for a discussion of oscillation detection statistics when a source also produces stochastic variations). Even in 1998, when CH Cygni was in a high state—presumably due to accretion onto the WD—and an oscillation would have been most likely to be present in the magnetic model, we did not find any oscillations.

By performing Monte Carlo simulations, we placed upper limits on the amplitude of any sinusoidal variations in the data. To make this test, we added oscillatory signals to our real data and measured the amplitude needed to produce a detectable signal. Because we searched for oscillations against a background of broadband (" red ") power, which is greater at lower frequencies, the upper limits are also a function of frequency. For example, in our 1998 July 19 observation, we could detect an oscillation with a semiamplitude of 2% or larger if its period was between 60 and 300 s. If the period was between 2500 and 3500 s, we could only constrain the semiamplitude of any oscillation hidden in the flickering to be less than 17%.

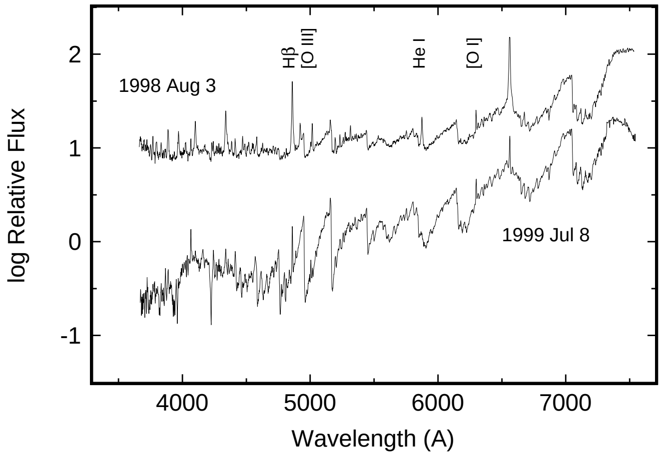

Fig. 5.—*Top*: High-state spectrum, before the proposed eclipse. *Bottom*: Spectrum during the eclipse. In the eclipse spectrum, the hot component is absent and the high-excitation He I emission line is gone, whereas the lower excitation lines from the outer nebula remain.

Table 3 lists the results of searching the period range of 450–550 s for all the light curves where the power spectrum could be well characterized by a power-law model.[2] We list oscillation amplitudes that were detectable at a 95% confidence level in 95% of the realizations. They range from 0.2% in the low states in 1997 and 2000 to 3.2% in the 1998 high state. To reduce the variance of the noise powers at high frequencies, and therefore improve our sensitivity to a possible quasi-periodic oscillation (QPO) near 500 s, we divided each light curve into 2–10 segments and averaged the power spectra from these individual segments. Applying this procedure, we did not find statistically significant QPOs above the background " red " power spectrum for any of the observations of CH Cygni listed in Table 3.

The nondetection of coherent oscillations at any frequency tested in either the high or low state, our limits on coherent oscillations near 500 s, and the lack of evidence for any QPOs near this period make the magnetic interpretation for CH Cygni questionable. As for the theoretical necessity of a strong magnetic field for jet production, Fender & Hendry (2000) found, for X-ray binaries, that the truncation of the inner disk by a strong magnetic field could actually inhibit the formation of a jet, not cause it. Therefore, we conclude that alternatives to the magnetic propeller model for CH Cygni should be explored.

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[2] The oscillation detection statistics are not meaningful unless there is an acceptable fit for the functional form of the broadband power. See the Appendix.

TABLE 3

Oscillation Upper Limits Near $P = 500$ s

Observation	Date (UT)	Pulse Fraction Upper Limit (%)	Amplitude Limit[a] (mmag)	Comments
3	1997 Aug 5	0.3	6.7	Optical low state
4	1998 Jul 19	2.5	54	Optical high state
6	1998 Jul 22	2.7	58	Optical high state
7	1998 Aug 19[b]	3.2	70	U, Optical high state
8	1999 Jun 12	0.4	7.7	Eclipse ingress
9	1999 Jun 13	0.5	10.6	U, Eclipse ingress
13	2000 Jun 22	0.2	5.1	Optical low state
14	2000 Jul 3	0.2	5.0	Optical low state

[a] Peak-to-peak oscillation amplitude corresponding to the pulse fraction upper limit.

[b] First part of light curve only, since exposure times changed during observation. The second light curve segment shows formally significant power in a restricted search between $P = 450$ and 550 s, but this power is probably an artifact, since there was broadband structure in the power spectrum beyond a simple power law that could not be fitted.

6. IMPLICATIONS FOR BRIGHTNESS-STATE CHANGES

In almost every type of interacting binary star (or other accreting system), disk accretion produces stochastic brightness variations. The flickering in CH Cygni disappeared during eclipse of the hot component (see § 4) and must therefore come from a region physically near the WD. Inhomogeneities in and around an accretion column in polars can produce stochastic variations (e.g., Warner 1995 and references therein), and Mikołajewski & Mikołajewska (1988) have suggested that brightness fluctuations in CH Cygni are due to interaction of the accreted material with a strong magnetic field. But no spin modulation has been found in CH Cygni (see § 5), so the flickering in this system is unlikely to be related to magnetism. Leahy & Taylor (1987) noted that the X-ray emission detected by *EXOSAT* could be due to either a disk boundary layer or shock-heated colliding winds. Fast stochastic variations (Ezuka et al. 1998, later confirmed variations with timescales as short as 100 s) support a disk boundary layer. Theoretically, a disk can form from the red giant wind in CH Cygni if the wind speed is $\lesssim 50$ km s^{-1} (for $P_{\rm orb} \approx 760$ days) or $\lesssim 30$ km s^{-1} (for $P_{\rm orb} \approx 14$ yr, taking a total system mass of 2 $M_\odot$ in each case; Livio 1988). Dyck, van Belle, & Thompson (1998) measure a stellar disk size for the red giant in CH Cygni of 10.4 mas. For a distance of 245 ± 50 pc (from the mode of the *Hipparcos* parallax probability distribution), this angular size corresponds to a stellar radius of approximately 270 $R_\odot$, which is reasonable for an M6-7 III giant. Schild et al. (1999) also estimate a radius of 280 ± 65 $R_\odot$, from the J and K magnitudes. The escape speed is therefore about 40 km s^{-1}. The red giant wind speed is probably less than the escape speed, and so it is reasonable to expect a disk to form. Thus, the most natural explanation for the fast fluctuations is disk flickering, and changes in the flickering can tell us about changes in the disk.

Looking back at Table 2, we see that the optical luminosity of the rapidly variable component, $L_{B,\rm var}$, increased by more than a factor of 20 between 1997 and the optical high state in 1998. Given this large increase, the physical process that produces the optical flickering must have been largely responsible for the overall optical brightening of CH Cygni (by roughly a factor of 7) between 1997 and 1998. The large increase in the luminosity of the flickering component therefore implies that the change to a high state was due to an increase in the accretion rate through the disk, $\dot{M}$.

One way to produce a change in $\dot{M}$ through a disk is via a dwarf nova–like thermal-viscous disk instability (e.g., Warner 1995 and references therein). The disk in CH Cygni could be much larger than disks in CVs, the time-averaged accretion rate could be higher, and it is formed from a wind rather than a stream. Duschl (1986a, 1986b) examined large symbiotic accretion disks theoretically and found that they are also likely to experience limit-cycle instabilities. The $\dot{M}$-Σ relations (where Σ is the surface density) have negative sloping sections in the temperature region where H is ionized, as in CVs, and also at lower temperatures, where the molecular opacity changes.[3] Again taking a distance of 245 ± 50 pc for CH Cygni, $M_V \sim -1$ in the 1979–1984 high state, $M_V \sim 1$ in the low state after the 1985 jet, and $M_V \sim 4$ at the extremely low point after the jet in 1997. These values are reasonable for dwarf nova high and low states, given that the disk in CH Cygni is likely to be large and that the red giant makes a significant contribution at V. The value of $L_{B,\rm var}$ is of the order of the luminosity expected from accretion onto a WD ($\sim 10^{32}$–10^{33} ergs s^{-1}), with a lower accretion rate onto the WD in 1997 compared to 1998. Furthermore, the expected recurrence time for an instability in a large disk, assuming an average accretion rate of $10^{-8} M_\odot$ yr^{-1} and an accretion disk radius on the order of tens of solar radii, is on the order of years.[4] This expected recurrence time agrees well with the timescale of state changes in CH Cygni. Finally, in the high state, the hot component in CH Cygni has an F-type supergiant spectrum, very similar to the high-state disks of dwarf novae in outburst.

There are, however, some major differences between the behavior of CH Cygni and that of dwarf novae in the optical. Instead of having the fast rise and exponential decay shape common to dwarf nova outbursts, the high states in CH Cygni tend to be plateaulike. CH Cygni's long-term light curve is also much more complex than long periods of quiescence with outbursts superposed.

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[3] Duschl (1986a, 1986b) considered large disks in main-sequence symbiotic stars, but his results are also relevant for WD symbiotics.

[4] The recurrence time is either approximately the viscous time at the outer edge of the disk for an outside-in outburst, or given by expression (3.29a) in Warner (1995), from Cannizzo, Shafter, & Wheeler (1988) for an inside-out outburst.

Bogdanov & Taranova (2001) explored an alternative hypothesis: that the long-term optical variations in CH Cygni (timescale of months to decades) are due to obscuration by dust. Several observations after the 1984 and 1996 optical flux declines revealed an increase in the column density of dust (e.g., Taranova & Yudin 1988, 1992; Munari et al. 1996; Bogdanov & Taranova 2001). The 1996 optical fading to the very low state, however, occurred 100–150 days before the increased production of dust (as indicated by a sudden change in $J-H$ color; Bogdanov & Taranova 2001), and the 1984 optical fading to the low state also occurred before the dust condensation in 1985–1987 (Taranova & Yudin 1988). Furthermore, the spectral changes described in Paper I are consistent with a decrease in the ionization state of the nebula, not obscuration of the entire system. Therefore, the optical fadings (and associated jet events) were either unrelated to the episodes of dust condensation, or even somehow caused the dust production.

The increase in the optical flickering luminosity in the high state indicates that the activity in this system is accretion-driven. Since the disk in CH Cygni (assuming one exists) is expected to be subject to the same instability as in dwarf novae (and possibly another; Duschl 1986a, 1986b), we propose that such instabilities drive the activity in CH Cygni as well. Since jets are sometimes associated with state changes in CH Cygni, collimated outflows could be related to the disk instabilities. An alternative model, in which material is expelled by a rapidly rotating magnetic field, requires that the WD have a strong magnetic field. We do not find evidence for such a field and therefore favor the disk instability scenario.

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APPENDIX

OSCILLATION DETECTION IN LIGHT CURVE WITH BROADBAND POWER

The presence of large-amplitude stochastic variations makes coherent oscillations, which are the hallmark of magnetic accretion, difficult to identify. In order to make any statistical statements about coherent oscillations, QPOs, or the quality of a model fit to the power spectrum, one must assume some distribution of the noise powers about the " true " power spectrum shape. Van der Klis (1989) found that for the neutron star binary GX 5-1, which flickers and has a QPO in the X-ray regime, the distribution of noise powers at a given frequency is well described by a χ^2 distribution about the mean value of the power at that frequency (averaged over thousands of observations). Deeter & Boynton (1982) predicted a χ^2 noise-power distribution on theoretical grounds for a " red " spectrum that is the integral of white noise. Since we do not have thousands of observations, we take the suggestion of van der Klis (1989) and assume a χ^2 distribution about the best-fit power law for each observation. The probability $\Pr(P_{\rm noise} > P)$ that the noise power in a single frequency bin will exceed the threshold value P is

$$\Pr(P_{\rm noise} > P) = Q(\chi^2|\nu) , \tag{A1}$$

with $\chi^2 = 2P/P_{\rm fit}$ and $\nu = 2$, where the χ^2 distribution with ν degrees of freedom is given by

$$Q(\chi^2|\nu) = \left[2^{\nu/2}\, \Gamma(\nu/2)\right]^{-1} \int_{\chi^2}^{\infty} t^{(\nu/2)-1}\, e^{-t/2}\, dt , \tag{A2}$$

and $P_{\rm fit}$ is the value of the model fit at the frequency of interest. Performing the integral, we get the well-known result $\Pr(P_{\rm noise} > P) = e^{-P/P_{\rm fit}}$. For a search of multiple frequency bins, the probability $\Pr(P_{\rm noise} > P)$ that at least one of the noise powers will exceed P is

$$\Pr(P_{\rm noise} > P) = 1 - \left(1 - e^{-P/P_{\rm fit}}\right)^{n_{\rm freq}} , \tag{A3}$$

where $n_{\rm freq}$ is the number of frequencies searched. A peak with power P in the power spectrum only indicates the presence of a coherent oscillation if this probability is small.

The original, full frequency-resolution power spectra provide the best sensitivity to a narrow (single frequency bin) feature in the power spectrum. Sensitivity to a broad feature (QPO), on the other hand, improves when power spectra produced from light-curve segments are averaged, as long as the width of the feature is larger than one frequency bin in the averaged power spectrum (van der Klis 1989). Using the notation of van der Klis (1989), averaging M power spectra reduces the variance in the combined power spectrum by a factor of MW, where W is an additional factor for binning in the frequency domain. The noise powers in the averaged and binned power spectrum are distributed like χ^2 with $2MW$ instead of 2 degrees of freedom and $\chi^2 = 2MWP/P_{\rm fit}$ (see van der Klis 1989, eq. [3.4]). Doing the χ^2 distribution integral in the general case, we find the probability for a noise power to exceed a threshold value P in a single frequency bin of a binned and averaged power spectrum,

$$(P_{\rm noise} > P) = Q(2MWP/P_{\rm fit}|2MW) = e^{-MWP/P_{\rm fit}} \sum_{n=1}^{MW} \frac{(MW)^{MW-n}(P/P_{\rm fit})^{MW-n}}{(MW-n)!} . \tag{A4}$$

The expression for a multiple-frequency bin search of the binned and averaged power spectrum is

$$(P_{\rm noise} > P) = 1 - [1 - Q(2MWP/P_{\rm fit}|2MW)]^{n_{\rm freq}} . \tag{A5}$$

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