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CH CYGNI. I. OBSERVATIONAL EVIDENCE FOR A DISK-JET CONNECTION

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ABSTRACT

We investigate the role of accretion in the production of jets in the symbiotic star CH Cygni. Assuming that the rapid stochastic optical variations in CH Cygni come from the accretion disk, as in cataclysmic variables, we use changes in this flickering to diagnose the state of the disk in 1997. At that time, CH Cygni dropped to a very low optical state, and Karovska et al. report that a radio jet was produced. For approximately 1 yr after the jet production, the amplitude of the fastest (timescale of minutes) variations was significantly reduced, although smooth, hour-timescale variations were still present. This light-curve evolution indicates that the inner disk may have been disrupted, or emission from this region suppressed, in association with the mass ejection event. We describe optical spectra that support this interpretation of the flickering changes. The simultaneous state change, jet ejection, and disk disruption suggest a comparison between CH Cygni and some black hole candidate X-ray binaries that show changes in the inner-disk radius in conjunction with discrete ejection events on a wide range of timescales (e.g., the microquasar GRS 1915+105 and XTE J1550−564).

Subject headings: accretion, accretion disks — binaries: symbiotic — instabilities — stars: winds, outflows — techniques: photometric

1. INTRODUCTION

Many astrophysical systems produce collimated jets, including young stellar objects, X-ray binaries and symbiotic stars, and active galactic nuclei. Livio (1997) suggested that there is a common formation mechanism for all jets and that they are all fundamentally accretion-powered. If these assertions are correct, then accreting white dwarf (WD) systems play a vital role in the study of jet phenomena, since WD disks are much more well understood than, for instance, black hole disks (see, e.g., Warner 1995). Furthermore, Zamanov & Marziani (2002) speculated that the relationship between WD and black hole jet sources could be significant enough that some symbiotic stars, including CH Cygni, can be considered "nanoquasars."

In stellar black hole systems, the presence of bipolar radio jets is related to the state of the accretion disk. Outflows may be present in the low/hard X-ray state but not in the high/soft state (e.g., Hjellming & Han 1995; Fender 2001). Transitions between states can also lead to discrete plasma ejections (Hjellming & Han 1995; Kuulkers et al. 1999; Fender et al. 1999a, 1999b; Fender & Kuulkers 2001). Collimated jets, however, have not been observed in cataclysmic variables (CVs; Knigge & Livio 1998), the most numerous and well-studied type of WD interacting binary. Although WD systems provide the best details on the structure of the disk, they have so far told us little about jets.

CH Cygni, on the other hand, is one of the most dramatic Galactic jet sources. At least three distinct sets of jet events have been recorded, in 1984–1985, 1994–1995, and 1996–1997 (Taylor, Seaquist, & Mattei 1986; Karovska, Carilli, & Mattei 1998; Crocker et al. 2001). An elongated radio structure from each of these ejections was detectable for several years (e.g., in 1986, 1995, and 1999; Crocker et al. 2001), and each jet event was associated with a period of optical activity. For all three events, jet production followed a sudden drop in the optical flux.

In this paper, we investigate the role of accretion in the production of jets in CH Cygni. The optical spectrum of CH Cygni is complicated by the presence of the red giant and nebular emission; examining rapid (timescales of minutes to hours) optical variations is one way to isolate emission from the accretion disk. Although the exact nature of stochastic optical variations observed in nonmagnetic CVs is not clear, they are generally considered the result of accretion onto a WD through a disk (e.g., Warner 1995). Proposed mechanisms for disk flickering include unstable mass transfer from the mass donor star, magnetic discharges, turbulence, and boundary layer instabilities (Bruch 1992). If a disk can form from the red giant wind,[1] the flickering in CH Cygni probably has a similar origin.

Between 1997 and 2000, we performed rapid optical photometric and optical spectroscopic observations of CH Cygni. We describe the complete data set in a companion paper (Sokoloski & Kenyon 2003, hereafter Paper II). In the present paper, we discuss observations from 1997, which provide information about the accretion disk during the production of a radio jet.

The paper is divided into six sections. After the initial description of the observations and fast-photometry results in § 2, we discuss the 1997 radio jet in § 3. In § 4 we interpret the flickering changes seen when a radio jet was produced as the result of disruption of the inner accretion disk, or suppression of the emission from this region. Several alternative interpretations are examined in § 5. We explore the implications of these results for jet formation in CH Cygni and, by extension, other WD accretors in § 6.

2. OBSERVATIONS AND PHOTOMETRIC RESULTS

We performed high time-resolution optical differential photometry at *B* and *U*, using the 1 m Nickel telescope at Lick Observatory between 1997 and 2000. In this paper, we

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[1] See Sokoloski & Kenyon (2003, hereafter Paper II) for a discussion of this point.

focus on observations from around the time of the 1997 radio jet. In addition, 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). See Sokoloski, Bildsten, & Ho (2001) for a description of photometric observing technique and instruments and Paper II for details of the CH Cygni data analysis.

Examples of high time-resolution light curves from 1997 and 1998 are shown in Figure 1. The first two observations, from 1997 April and June, show low-amplitude ($\Delta m < 0.15$ mag), smooth variations and have power spectra that generally cannot be fitted with power-law models (similar light curves were reported by Rodgers et al. 1997 as early as 1996 June). A few months later, in 1997 August, the fractional flickering amplitude had not changed, but the strength of the fastest (minute timescale) variations increased. The light curve then had a more jagged appearance. The power spectrum of this observation had the standard power-law shape found in nonmagnetic CVs. One year later, in 1998 July and August, the variability amplitude increased to the typical high-state value of $\Delta m \sim 0.5$ mag, while the power spectrum retained its power-law shape. Figure 2 compares a power spectrum from the postjet period when only smooth variations were seen with a power spectrum from a few months later, when minute timescale variations returned.

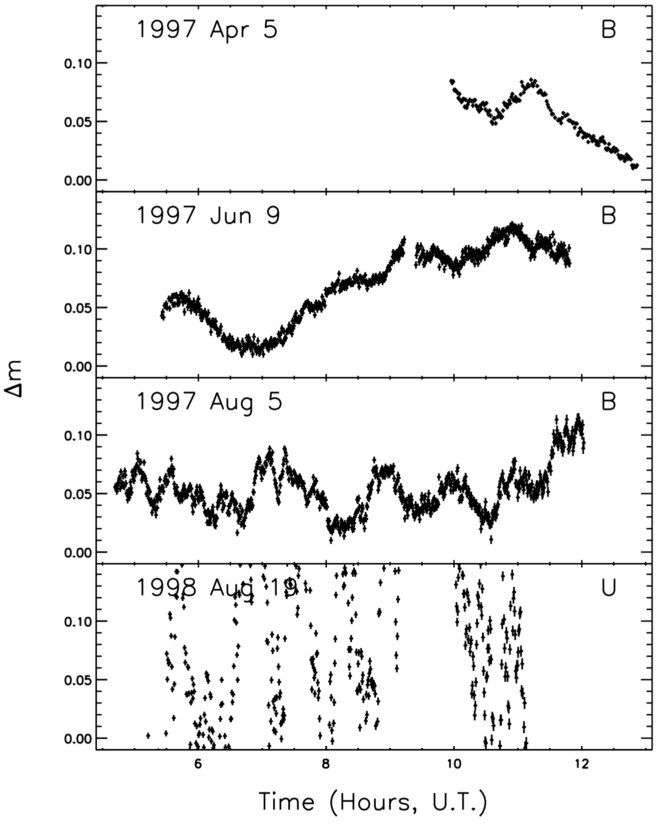

FIG. 1.—Example of light curves from 1997 and 1998 (from Paper II), plotted on the same scale for direct comparison. The light curves evolve from showing smooth, low-amplitude variations after the ejection of the radio jet in 1996 (see § 3), to full CV-like flickering more than 1 yr later (the amplitude of the variations in 1998 span 3 times the magnitude range shown).

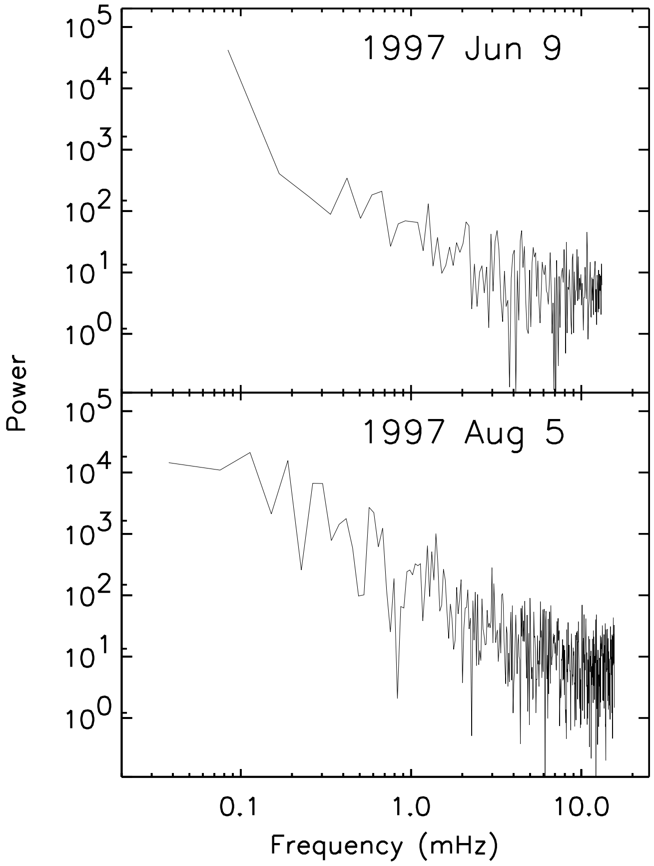

FIG. 2.—Example of power spectra (normalized by the total number of source counts in each observation) from 1997. The power spectrum during the early production of the 1997 radio jet (*top*) cannot be fitted with a simple power-law model. A power spectrum from several months later (*bottom*) is well described by a power-law model.

3. THE 1997–1999 RADIO JET

On the basis of the radio observations reported by Karovska et al. (1998), CH Cygni began producing a radio jet sometime before 1997 January, when they first detected extended radio emission. The radio flux density began to rise in 1997 April, at the same time as we started our photometric observing campaign. Radio extension associated with the radio brightening was later confirmed by M. Karovska (2002, private communication); Eyres et al. (2002) discuss the mass outflow from CH Cygni during and after 1998. Figure 3 shows the long-term optical light curve of CH Cygni (kindly provided by the AAVSO), with the times of our fast photometric observations marked, and the early development of the radio jet at 22 GHz (Karovska et al. 1998).

We can estimate the speed of the jet material, and hence the approximate time when the material was expelled, if we assume that the radio elongation measured in 1999 by Crocker et al. (2001) was from the 1997 ejection. The elongation measured by Crocker et al. (2001) was primarily south of the central radio source. Either the ejection was one-sided, or the emission from a northern component had faded by 1999 September. Comparing the initial report of north-south elongation at 0''.25 resolution in 1997 January (at 15 GHz with the VLA, in BnA configuration; Karovska et al. 1998) with the approximately 1''.7 north-south

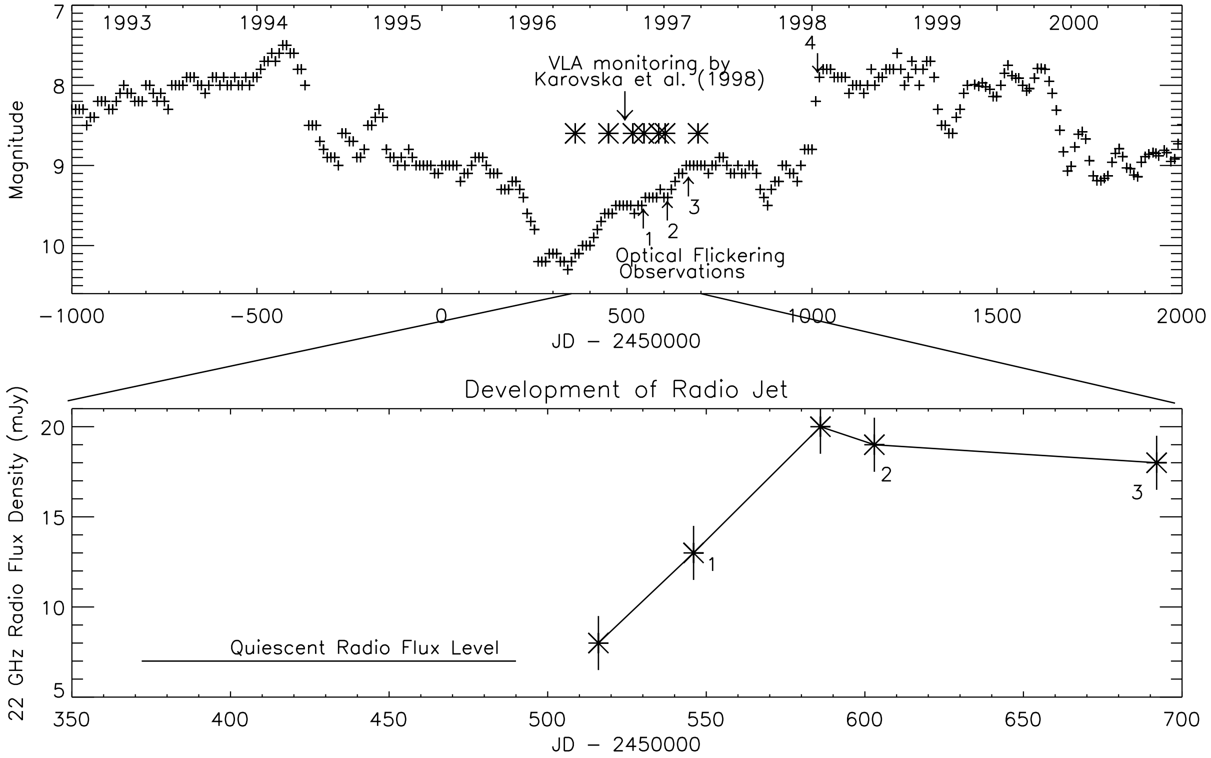

FIG. 3.—*Top*: Long-term optical light curve of CH Cygni, from the AAVSO. Four flickering observations in 1997 and 1998 are marked with arrows, and the period of radio monitoring by Karovska et al. (1998) is marked with stars. *Bottom*: Shows 22 GHz radio flux densities, from Karovska et al. (1998). Detection of spatial extension in a follow-up VLA observation confirmed that the rise in the radio emission was indeed due to the production of a jet (M. Karovska 2002, private communication).

structure detected by Crocker et al. (2001) in 1999 September (at 8.4 GHz with VLA in A configuration), we estimate a growth rate of roughly $1\farcs5$ in 990 days, or 650 km s^{-1} for a distance of 245 ± 50 pc (from the mode of the *Hipparcos* parallax probability distribution). In making this estimate, we took the southerly extension to be approximately $0\farcs2$ in 1997 January and measured the 1999 jet size between the central radio component and the maximum extent of the 3 σ contour (from the map of Crocker et al. 2001). At that rate, the jet took roughly 130 days to expand the initial $0\farcs2$, putting the initial expulsion of material around JD 2,450,330 (1996 August–September). This date for the initial ejection is only approximate, since we do not have a map of the radio emission in 1997, we do not know how the sensitivities of the 1997 and 1999 observations compare, and the 1997 and 1999 observations were done at different frequencies. Even so, our estimate puts the origin of the jet roughly within a few months of the 1996 optical fading and the beginning of the period where only smooth variations were apparent in the optical light curves (as in the top panels in Fig. 1). It is therefore likely that the flux drop, the jet ejection, and the change in the optical flickering were all related.

In CH Cygni, the production of jets generally appears to follow a sudden drop in the optical flux. In 1984–1985, the 14.9 GHz radio flux density increased by a factor of 30 as the initial radio structure grew to $0\farcs4$ (Taylor et al. 1986). The production of this jet followed a decrease in the visual flux of over 1.2 mag in less than 50 days (AAVSO). The 1995 radio jet may have been related to a similar optical decline in 1994 (Crocker et al. 2001), and the 1997 jet followed a 1 mag drop in about 100 days (AAVSO). In 1986 Crocker et al. (2001) found that the core of the radio emission had a positive spectral slope, whereas the extended regions had a negative spectral slope consistent with nonthermal synchrotron emission from relativistic electrons in a magnetic field. They suggested that the electrons were accelerated in a shock as the ejecta collided with nebular material from the circumstellar wind. In 1999 they found similar negative spectral index emission from the extended region, presumably associated with the 1997 jet ejection.

Although there are some similarities between the ejections in 1984–1985 and 1997, there are also differences. In 1984–1985, the 14.9 GHz radio flux density peaked roughly 6 months after the optical drop. The delay between the optical decline in 1996 and the subsequent radio rise was approximately 1 yr. Correspondingly, the expansion velocity estimated for the 1985 jet of approximately 1300 km s^{-1} (using the same method of comparing the distance between the central radio component and the farthest 3 σ contour and taking $d = 245$ pc) is roughly twice our estimate of 650 km s^{-1} for the 1997 jet (see above). Moreover, in 1997 the optical flux decreased from an already low state to a much lower level. So either the system brightness was affected by dust obscuration at this time, there was an intrinsic fading of the red giant (as suggested by Skopal 1997), or the 1996 fading put the disk into a new, very low state.

4. DISK DISRUPTION

In almost every type of interacting binary star (or other accreting system), disk accretion produces stochastic brightness variations. Assuming that the rapid stochastic variations in CH Cygni are due to disk accretion,[2] changes in the flickering can tell us about changes in the disk. Although the physical mechanism responsible for disk flickering is not well understood, several possible models suggest that the fastest variations come from the innermost regions of the disk. This radial dependence arises because both the viscous and dynamical times increase with disk radius. For example, Lyubarskii (1997) examined a model in which the viscosity parameter α varies on the local viscous timescale. Variations that originate at different radii propagate inward to produce a "red-noise" spectrum of variations at the boundary layer. Although fluctuations in CVs (and CH Cygni) are too fast to be strictly tied to viscous timescale variations in a thin disk, extensive timing studies of X-ray binaries and active galactic nuclei by Uttley & McHardy (2001) support this type of "propagation" model. As another example, Geertsema & Achterberg (1992) found that in a geometrically thin, differentially rotating disk, magnetohydrodynamic turbulent energy fluctuates at roughly the Keplerian orbital frequency (i.e., on the dynamical time). Although the observed flickering will also be influenced by the dissipation through small turbulent eddies, the increase in the timescale of fluctuations farther out in the disk could introduce a radial dependence into the speed of stochastic variations.

Observationally, numerous authors have associated the dominant source of minute-timescale flickering in CVs with the inner-disk and/or WD surface (e.g., Horne & Stiening 1985; O'Donoghue, Fairall, & Warner 1987; Horne et al. 1994; Bruch 2000). In several FU Ori pre–main-sequence stars, which have larger inner-disk radii, the disk emission varies on timescales closer to a day or less (e.g., Kenyon et al. 2000). In neutron star X-ray binaries, which have smaller inner-disk radii, stochastic X-ray variations are seen with subsecond timescales (van der Klis 1995). In black hole X-ray binaries, the low-frequency quasi-periodic oscillation (QPO) may shift when the inner-disk radius changes, in the sense that larger inner-disk radii produce lower frequency QPOs (e.g., XTE J1550−564, GRS 1915+105: Sobczak et al. 2000a; Varnière, Rodriguez, & Tagger 2002; Muno, Morgan, & Remillard 1999).[3] The general connection between proximity to the central object and variation speed is supported further by the recent discovery that some QPOs in CVs are analogous to those in low-mass X-ray binaries, but 4 orders of magnitude slower (Mauche 2002). Thus, the dependence of variation timescale on the location in the disk is evident both in the comparison among systems with different size disks and within an accretion disk in a given type of system (in the sense that slower variations come from the larger disk radii, and vice versa).

In CH Cygni, the fastest (i.e., minute timescale) optical variations were absent when the 1997 radio jet was ejected; rolling, hour-timescale fluctuations remained. Rodgers et al. (1997) reported similar smooth, low-amplitude variations between 1996 June and October, after the drop in optical flux that we have associated with the collimated jet ejection. Given the relationship between disk radius and variability timescale described above, the disappearance of the fastest variations indicates that the innermost disk was disrupted (or emission from it suppressed) around the time when the radio jet was produced. Since Rodgers et al. (1997) detected smooth variations as early as 1996 June, the drop in optical flux just before that time may have been due to the disappearance of the inner disk. The reappearance of rapid variations as the flux rose in 1997 August would then indicate that the inner disk was being rebuilt.

The timescales of both the smooth variations in 1996–1997 and the return of the more rapid fluctuations in late 1997 agree with the disk disruption picture. If, based on the postjet light curves in 1996–1997, we take ~1 hr as the dynamical time at the inner edge of the truncated disk, we infer an inner-disk radius after the jet ejection of $\sim 1\ R_\odot$,

$$R_{\rm inner} \sim 1\ R_\odot \left(\frac{t_{\rm dyn}}{1\ {\rm hr}}\right)^{2/3} \left(\frac{M_{\rm WD}}{0.5\ M_\odot}\right)^{1/3} . \tag{1}$$

For an accretion rate of $10^{-9}\ M_\odot\ {\rm yr}^{-1}$ and $\alpha = 0.03$ (for a low-state disk; Warner 1995), $R_{\rm inner} \sim 1\ R_\odot$ corresponds to a viscous time of roughly 1 yr,

$$t_{\rm visc} \sim 1\ {\rm yr} \left(\frac{\alpha}{0.03}\right)^{-4/5} \left(\frac{\dot{M}}{10^{-9}\ M_\odot\ {\rm yr}^{-1}}\right)^{-3/10} \left(\frac{R}{R_\odot}\right)^{5/4} \tag{2}$$

(see Frank, King, & Raine 1992). We expect the disk to be rebuilt on the viscous time at the inner edge, and in fact, the fastest variations return after roughly 1 yr.

Our velocity extrapolation indicates that the jet material was expelled during the 1996 flux drop. We show an example of spectra from before and after the optical decline in Figure 4. Comparing line equivalent widths, and taking into account the factor of 3 decline in the continuum (at V), the high ionization state He I $\lambda5015$ line decreased in strength after the initial jet ejection, while the moderate ionization state Hβ, [O III], and [Ne III] line strengths stayed approximately constant. The [O I] line, which is often associated with jets in pre–main-sequence stars, increased in strength. The equivalent width changes are summarized in Table 1. The fact that the He I line decreased, but did not disappear, indicates that there may have been a second source of

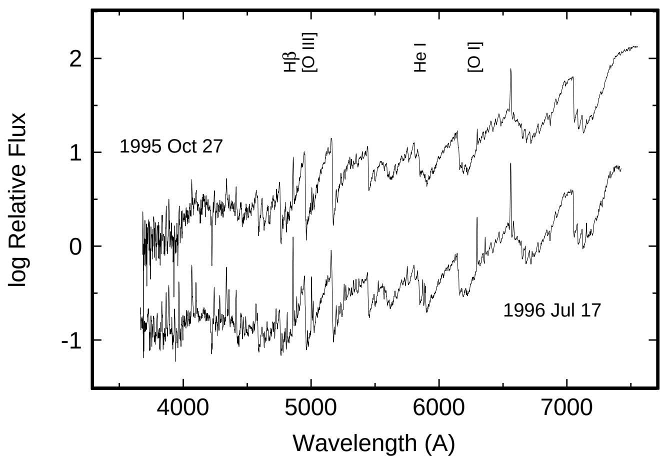

FIG. 4.—*Top*: Spectrum from 1995 October, in the low state before the 1996/1997 radio jet was produced. *Bottom*: Spectrum from 1996 July, after the drop to the very low state. The high-excitation He I emission-line flux decreased, whereas the moderate-excitation Hβ, [O III], and [Ne III] line fluxes remained roughly constant. [O I], which is a jet line in pre–main-sequence stars, is strengthened.

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[2] See Paper II for a detailed discussion of this point.

[3] The QPO frequency in GRO J1655−40, however, has the opposite behavior, possibly due to relativistic effects (Sobczak et al. 2000a; Varnière et al. 2002).

TABLE 1

LINE EQUIVALENT WIDTHS (EWS) BEFORE AND AFTER JET EJECTION

Emission Line	1995 Oct 27 (EW)	1996 Jul 17 (EW/3)[a]	Flux Change
He I λ5015 Å	3	2	Decreased
Hβ	15	16.7	~No change
[O III] λ5007 Å	5	5	No change
[Ne III] λ3968 Å	6	6	No change
[O I] λ6300 Å	2	4.5	Increased

[a] EW divided by 3 on 1997 October 27 to take into account a factor of 3 decrease in continuum flux and to allow for direct comparison between dates.

photons capable of photoionizing He I ($\chi = 24.6$ eV), such as shock-heated colliding winds or the WD surface. Nevertheless, the equivalent width changes are consistent with a decrease in the ionizing flux from the hot inner disk.

5. ALTERNATIVE INTERPRETATIONS

We propose that the minute timescale variations disappeared in 1997 because the inner accretion disk was disrupted, or emission from this region decreased, when the radio jet was produced. There are other alternatives. In 1997, the fastest variations from the disk could have been hidden rather than absent. For example, opaque material could have blocked the accretion disk. If the accreting WD ejected material equatorially before producing the jet (as in some other jet sources, e.g., SS 433; Paragi et al. 2002), perhaps disk-blocking dust clouds could have formed. In this picture, the smooth variations would be due to flickering FUV or soft X-ray light that is blocked from direct view but is seen via reprocessing in the nebula, which acts as a low-pass filter. The smooth light curves from late 1996 (Rodgers et al. 1997) and early 1997 (§ 2) are reminiscent of the Balmer line variations in RS Oph, which presumably originate in the nebula (Sokoloski 2003). However, the nebula would need to have a density $n_e \gtrsim 10^9$ cm^{-3} for the H recombination time to be on the order of hours ($n_e \gtrsim 10^{10}$ cm^{-3} for minutes). Measured nebular densities for CH Cygni tend to range between 1 and 3 orders of magnitude lower (e.g., Hack et al. 1986; Mikołajewska, Selvelli, & Hack 1988).

Densities in the disk, on the other hand, are much higher. If, instead of coming directly from the inner disk, the flickering optical light has been reprocessed in the outer disk, then the change in character of the light curves in 1997 could be due to a change in the reprocessing medium. If the density in the reprocessing site suddenly decreased, the recombination time would increase, and the fastest variations would be smeared out. But then the change we have observed would still indicate a change in the accretion disk in conjunction with the production of a radio jet.

Finally, if the accretion is diskless, the frequency content of the flickering could reflect the size distribution of the blobs of accreted material. It is unclear, however, why the size distribution of accreted blobs would change when a jet is produced. We therefore favor the disk disruption scenario over any of these other models.

6. IMPLICATIONS FOR JET FORMATION

We have described observations that indicate that the accretion disk was involved in jet production in CH Cygni. In particular, the disappearance of the fastest flickering implies that material from the innermost part of the disk was removed, or that emission from this region decreased. The removal of material, and the associated energy and angular momentum, from the inner disk implies that the jet was accretion-powered. Several other authors have proposed that the jets from CH Cygni originate in an accretion disk, or are the result of ejection of the inner disk (e.g., Solf 1987).

In their study of persistent X-ray binaries, Fender & Hendry (2000) found that similar-strength radio emission, presumably from jets, can exist in both neutron star and black hole systems. Thus, neither a black hole nor a compact star surface is necessary for jet production in these systems. On the other hand, they do not detect radio-jet emission from systems in which the inner disk is truncated by a strong magnetic field. Thus, it appears that the inner accretion disk is involved in, and possibly responsible for, jet formation in X-ray binaries. Our observations of changes in the accretion disk in CH Cygni indicate that for CH Cygni also, and therefore possibly for WD jet sources generally, the inner disk is closely linked to the bipolar ejection of material.

In CH Cygni, the production of jets appears to follow a sudden decline in the optical flux. The jet production mechanism, however, is not well understood. Taylor et al. (1986) proposed that super-Eddington accretion caused the collimated outflow, but *IUE* observations obtained by Mikołajewska et al. (1988) showed that the WD in CH Cygni was never close to the Eddington limit. Mikołajewski & Mikołajewska (1988) proposed that the jets are driven by rotational energy from the WD but, as we discuss in Paper II, there is little evidence that a strong surface magnetic field is present. It is therefore difficult to extract this rotational energy. Livio (1997) proposed that WD jets need a source of energy in addition to disk accretion, such as the nuclear shell burning thought to exist in supersoft X-ray sources (some of which have persistent jets: Southwell, Livio, & Pringle 1997; Livio 1997, and references therein), or a hot boundary layer between the disk and WD surface. CH Cygni has a low enough WD luminosity that nuclear burning is unlikely to be a significant source of energy. Variations on a timescale as short as ~100 s in the hard X-rays (Ezuka, Ishida, & Makino 1998; Leahy & Taylor 1987), as well as the high ionization-state optical and UV emission lines, suggest that it may, however, have a boundary layer.

The disk in CH Cygni is probably more similar to CV disks than disks that involve an advection-dominated accretion flow (ADAF), or other structures that have been suggested for black hole systems (such as advection-dominated inflow-outflow solutions [ADIOS], or "sphere + disk" Comptonization models: Narayan & Yi 1995; Esin et al. 1998; Blandford & Begelman 1999; Wilms et al. 1999). Nevertheless, our observations of the flickering in CH Cygni show that the inner radius appears to change when a jet is produced, as seen in some X-ray binaries. X-ray spectral fitting of the black hole X-ray transient XTE J1550−564 indicates that the disk inner radius increased at the beginning and end of an X-ray outburst at the same time that material was ejected (Sobczak et al. 2000b; Fender & Kuulkers 2001). In the black hole candidate GRS 1915+105, the inner disk was repeatedly evacuated when material was ejected (Belloni et al. 1997a, 1997b; Feroci et al. 1999).

Belloni et al. (1997a) suggest that a dwarf nova–like disk instability may be responsible for the observed limit cycle behavior and associated mass ejections of GRS 1915+105. In pre–main-sequence stars as well, the strength of the collimated outflow appears to be associated with the state of a thermally unstable accretion disk (Hartmann & Kenyon 1996). In Paper II, we propose that the activity in CH Cygni may also be driven by an unstable disk. Thus, although the inner disks around black holes and pre–main-sequence stars may be quite different from the inner disks around accreting WDs, the physics of jet ejection provides a link between them.

If discrete ejections are associated with state transitions in an unstable disk, it is still not clear whether disk thermal instabilities (DTIs) lead to collimated ejections or vice versa. Fender & Hendry (2000) suggest that in X-ray binaries, the ejections are a byproduct of an extreme physical change in the accretion flow. We mention one possible case in which a jet (say, due a centrifugally driven wind, such as in the Blandford & Payne 1982 bead-on-a-string model) leads to a DTI. Knigge (1999) showed that the disk temperature profile is modified with the addition of either a radiation-driven or centrifugally driven wind. In either case, the central temperature in a disk + wind system is lower, sometimes significantly, than a disk alone. Theoretical calculations of CV disk winds have shown that the mass-loss rate in the wind increases with disk luminosity for a bright disk (Proga 1999), so a high-state disk produces a strong wind. The presence of a strong enough disk wind from the inner disk, or a centrifugally driven jet, could therefore potentially trigger an inside-out cooling wave.

In summary, there are some intriguing observational similarities between CH Cygni and X-ray binaries with neutron star or black hole accretors. Both CH Cygni and X-ray transients can eject hot plasma when the systems change state. In CH Cygni, the jet ejections are associated with the sudden drop from an optical high state to an optical low state. In this paper, we have described a second similarity: changes in CH Cygni's light curve that suggest that emission from the inner disk decreased substantially when a jet was produced, possibly due to the evacuation of this region. These observational similarities support the idea that jets can form in the same way in different types of systems.

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