PROPELLERS – A NEW CLASS OF INTERACTING BINARIES

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Abstract. CH Cyg and MWC 560 are very peculiar symbiotic binaries consisting of an M giant and a white-dwarf companion. The systems have many features in common. In particular, both show occasional eruptions with sub-Eddington luminosity accompanied by flickering activity, and appearance of high-velocity jets. We present arguments that objects like CH Cyg and MWC 560 form a new subclass of interacting binaries distinguished by the presence of wind accreting magnetic white dwarfs.

1. CH Cygni and MWC 560 as Binary Systems

CH Cyg is a long-period, $P_{\rm orb} = 15.6\,{\rm yr}$, eclipsing binary which contains an SRa variable (M6–7 III), and a white-dwarf companion (Mikołajewski *et al.* 1987; Mikołajewski *et al.* 1988). The length of the orbital period suggests the M giant should not fill its Roche lobe. This picture is supported by available optical and IUE data. An M6–7 giant filling its Roche lobe will transfer matter at such a high rate, that the accreting material will burn steadily on the white-dwarf surface giving rise to a large luminosity, $L_{\rm h} \sim 1000$–$50\,000\,{\rm L}_{\odot}$, and a very high effective temperature,

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$T_{\rm eff} \sim 10^5$ K (Mikołajewska & Kenyon 1992), entirely inconsistent with observations (Mikołajewski *et al.* 1988; Mikołajewski & Mikołajewska 1994). Thus, in the following we assume that the giant never fills its tidal lobe, and the white-dwarf secondary accretes material from a stellar wind.

The case of MWC 560 is more complicated. The optical spectrum is dominated by narrow emission lines of singly ionized metals (Kolev & Tomov 1993). Radial velocities of these lines measured in our spectra obtained in 1990–94, do not show any changes related to orbital motion, while they do follow the orbital motion in CH Cyg (Skopal *et al.* 1989). The lack of evidence for orbital motion, and the jets expanding practically along the line of sight (see below) suggest a very low orbit inclination, $i \sim 0°$. On the other hand, analysis of the photographic light curve derived from Sonneberg plates collected in the period 1930–1990 (Luthardt 1991) revealed sharp 1 mag maxima occurring at ~1900 d intervals. A similar periodicity was recently found by Doroshenko *et al.* (1993). We attribute this periodicity to the orbital motion of MWC 560. The maxima of the light curve may be due to increased activity of the accreting component while passing the periastron in an elliptical orbit. As in the case of CH Cyg, the adopted orbital period is too long for the giant component – classified as M4–5 III (Thakar & Wing 1992) – to fill its tidal lobe.

Basic parameters of both systems are collected in Table 1.

TABLE 1. Binary characteristics

	CH Cygni	MWC 560
Orbital period:	5700 d	~ 1900 d
Inclination:	~90° (eclipses)	~0° (no orbital motion)
Eccentricity:	~0.5	high?
Cool component:	M6–7 III; SRa	M4–5 III
	$\dot{M}_{\rm cool} \sim (1\text{–}4)\ 10^{-7}\ {\rm M}_\odot\ {\rm yr}^{-1}$	???
Hot component:	wind accreting magnetic white dwarf	wind accreting magnetic white dwarf

2. Activity and Jets

The hot components in both systems show very spectacular activity. In CH Cyg, we deal with irregular outbursts, during which the luminosity of the hot component varies by a factor of 10^4, while in MWC 560 the hot component is always relatively luminous, and its brightness changes by a factor of ~3 to 4. Nevertheless, the main characteristics of their activity show striking similarities (Table 2). These are: (1) presence of a blue A–B type continuum veiling the M giant absorption features in the optical; (2) appearance of H I Balmer emission lines and numerous emission lines of ionized metals; (3) rapid variability (flickering) on time scales from minutes to hours; (4) appearance of rapid jets and bipolar outflows.

TABLE 2. Basic Properties of Activity

	CH Cygni	MWC 560
Luminosity:	sub-Eddington $L_{\rm max} \sim 300\,{\rm L}_\odot$ A–B type continuum + "iron curtain" with variable τ; H I line & continuum emission	sub-Eddington $L_{\rm max} \sim 300$–$1000\,{\rm L}_\odot$ A–B type continuum + "iron curtain" with variable τ; H I line & continuum emission
Light curve:	low & high activity stages, long inactive periods exist	high activity stages appear periodically with $P \sim 1900^d$
Flickering:	only during active phase; coherent periodic component $A \sim 5\%$, $P \sim 8\,{\rm min}$	always present; coherent periodic component $A \sim 5\%$, $P \sim 1$ hour
Jets:	accompanying *high* → *low* state transition: $v \sim 800\,{\rm km\,s^{-1}} \sim v_{\rm esc}(R_{\rm m})$ ⊥ orbital plane	slow continuous: $v \sim 200$–$2000\,{\rm km\,s^{-1}} \sim v_{\rm esc}(R_{\rm m})$ rapid occasional at max: $v \sim 2000$–$7000\,{\rm km\,s^{-1}} \sim v_{\rm esc}(R_{\rm WD})$ ⊥ orbital plane

MWC 560 became very fashionable in 1990, when Tomov *et al.* (1990) discovered variable high-velocity ($\sim$2000 to 6000 km s^{-1}) blueshifted absorption components in H I Balmer lines. A similar effect was found in the "iron curtain" features observed in the UV (Michalitsianos *et al.* 1991). This phenomenon was interpreted as due to expansion of highly collimated, unstable jets ejected along the line of sight (Tomov *et al.* 1992; Shore *et al.* 1994). Since 1990 MWC 560 has shown various symptoms of activity. Moreover, all – rather sporadic – spectroscopic and photometric observations made before 1990 also revealed some kind of activity, although none of these observations was done during the sharp maxima of the photographic light curve.

A detailed analysis of the photometric behavior of CH Cyg over a century (1885–1988) showed that, except for the period 1963–1994 when the hot component experienced a series of outbursts, the system remained inactive (Mikołajewski *et al.* 1990a). The light curve for the largest 1977–86 outburst suggests that CH Cyg oscillates between a *high* and a *low* accretion stage. This resembles the light curve of MWC 560. The *high* state of CH Cyg, observed as a flat maximum of the light curve during 1981–1984, corresponds to the sharp maxima of MWC 560. However contrary to CH Cyg, the hot component of MWC 560 is always active, although it spends most time in the *low* state.

The active phases in both systems are characterized by flickering. The flickering may have low-amplitude periodic components (Mikołajewski *et al.* 1990b; Michalitsianos *et al.* 1993).

The most spectacular phenomenon is, however, the occurrence of jets. In CH Cyg the jet features were first detected in VLA radio images (Taylor *et al.* 1985, 1988), and later also in optical emission lines (Solf 1987; Leedjärv *et al.* 1994). In MWC 560 the jet which is approaching practically along the line of sight, can be monitored by observations of the blueshifted absorption components – well separated from the emission components – of H I Balmer lines, and in the "iron curtain" features in the UV (Tomov *et al.* 1994). In both systems, the jets seem to be related to transitions between the *high* and the *low* stage of accretion. In CH Cyg jets developed just after a sudden drop from the high to the low state in July 1984. MWC 560 showed quasi-stationary outflow with moderate velocities, $\sim$200 to 2000 km s^{-1}, in the low state, before and after the 1990 maximum (Wachter *et al.* 1994; Tomov *et al.* 1994), while in the high state in 1990 occasional jets with high velocity, $\sim$2000 to 7000 km s^{-1}, and time scales of order of a few hours were observed. In both systems the jets seem to be highly collimated and moving nearly perpendicularly to the orbital plane.

3. Accretor–Propeller Model

The active phases (outbursts) in CH Cyg and MWC 560 have many features in common, which suggests similar nature of the active components and mechanisms of their activity. The presence of flickering, and the appearance of highly collimated jets in the sub-Eddington accretion regime, indicate the presence of a strong magnetic field in the accreting component. We attribute the periodic flickering component in each system to the spin period of the magnetic white dwarf. The presence of a rotating disk-like envelope and an extended pseudo-photosphere, points to the presence of a centrifugal barrier (propeller action). Finally, the occurrence of low- and high-activity stages, the appearance of jets during the transition to the low state in CH Cyg, and episodic ejection of very high-velocity jets during high states in MWC 560, indicates *propeller* ↔ *accretor* transitions.

In our study we assume, following Lipunov (1987), that the rotational luminosity: $L_{\rm rot} \propto R_{\rm t}^3$, where the distance scale $R_{\rm t}$ should be close to the corotation radius, $R_{\rm c}$, in the *accretor* state, and to a magnetosphere radius, $R_{\rm m}$, in the *propeller* state. Unfortunately, the magnetosphere radius so far is, but poorly, known in the propeller state, and can highly deviate from the standard expression for the Alfven radius adopted in most studies (Lipunov 1987). Including accretion and assuming that for some critical values, $R_{\rm m} = R_{\rm cat}$ ($\sim R_{\rm c}$) and $\dot{M} = \dot{M}_{\rm cat}$, the rotator is in *catastrophic* equilibrium, and a small change in the accretion rate makes the rotator pass from *propeller* (low) into *accretor* (high) state and vice versa. The luminosity of the rotator will interchange between two values:

$$L_{\rm prop} = \frac{GM_{\rm WD}\dot{M}_{\rm cat}}{R_{\rm cat}} + \kappa_{\rm t}\mu^2\frac{\omega}{R_{\rm cat}^3} \quad \Longleftrightarrow \quad L_{\rm accr} = \frac{GM_{\rm WD}\dot{M}_{\rm cat}}{R_{\rm WD}} + \kappa_{\rm t}\mu^2\frac{\omega}{R_{\rm cat}^3}$$

where $\kappa_{\rm t} = 2/3\sin^2\beta$, μ is the magnetic dipole moment, β the angle between the magnetic and rotational axes, and ω the angular velocity of the rotator. If $L_{\rm prop}$, $L_{\rm accr}$, $R_{\rm WD}$, $M_{\rm WD}$, and ω are known, practically all parameters of the rotator can be estimated (Mikołajewski *et al.* 1990b; Mikołajewski & Mikołajewska 1994). The inclination of the rotator, β, remains the only free parameter of our model (Table 3).

TABLE 3. **Parameters of Oblique Rotator**

	CH Cygni	MWC 560
B	$\sim 10^7$–10^8 G	$\sim 10^7$–10^8 G
$P_{\rm rot}$	$\sim$8 min	$\sim$ 1 hour
$\dot{M}_{\rm cat}$	a few 10^{-8} M$_\odot$ yr^{-1}	a few 10^{-8} M$_\odot$ yr^{-1}
$R_{\rm cat}$	$\sim$ a few $R_{\rm WD}$	$\sim$ a few $R_{\rm WD}$
β	large? ($\sim$45°)	small? ($<$5°)

In CH Cyg, the jets appeared only after the *accretor* → *propeller* transition, and almost all matter accumulated around the rotator was expelled. It suggests very strong propeller action along the rotational axis, i.e., in the direction of maximum gradient of magnetic pressure changes, and thus $\beta \sim 45°$ (Illarionov & Sunyaev 1975). On the other hand, sporadic jets which appear during *high* (accretor) stages of MWC 560, have very high velocities comparable to the escape velocity from the white-dwarf surface. Thus the jets appear to be driven by super-Eddington accretion in the accretion columns. Simultaneously, the observed high collimation of the jets requires a magnetic axis nearly parallel to the rotational axis ($\beta < 5°$).

CH Cyg and MWC 560 seem to form a new subclass of interacting binaries distinguished by a wind accretion onto a magnetic white dwarf. The salient characteristic of the class are: (1) sub–Eddington brightness at maximum; (2) presence of flickering; (3) high and low stages of activity; (4) ocassional appearance of bipolar outflows or jets. Because these objects spend most time in the propeller (low) state, and the ejection of jets is due to specific propeller action, we propose to call them *propeller stars* or *propellers*. Other possible candidates are R Aqr, *o* Cet, and the symbiotic recurrent novae T CrB and RS Oph. R Aqr is a well known symbiotic Mira with jets, while the remaining candidates are the only known symbiotic stars with flickering.

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