Magnetic propeller in symbiotic stars

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Abstract. Rapidly spinning magnetic white dwarfs in symbiotic stars may pass through the propeller stage. It is believed that a magnetic propeller acts in two such stars CH Cyg and MWC 560. We review a diversity of manifestations of the propeller there. In these systems in a quiescent state the accretion onto a white dwarf from the strong enough wind of a companion star is suppressed by the magnetic field, and the hot component luminosity is low. Since the gas stored in the envelope eventually settles to the corotation radius the star-propeller reveals itself by long-time outbursts, short-time brightness dips, strong amplitude flickering, ejection of a powerful wind and jets. The envelope appears to be stratified and inhomogeneous because of the shock pumping of the propeller. At this stage, at which catastrophic transitions to the accretion stage and back are possible, the release of energy and angular momentum of the white dwarf is maximum. Using this property, we estimate the magnetic field strength of the white dwarfs in CH Cyg and MWC 560 to be of order $10^8$ G.

The most spectacular property of these stars — jets — is inherently connected with the propeller. This suggests hydromagnetic models of jet acceleration.

1. Introduction

In the course of spin deceleration a neutron star having a strong magnetic field may pass through an evolution stage of the propeller before accreting gas from the surroundings and appearing as a bright X-ray source (Schwartzman 1971, Illarionov & Sunyaev 1975). However, from observations propellers are not known reliably. The transfer from the propeller stage to accretion one is abrupt. Such transfers are suggested only in the low mass X-ray binaries Aql X1 and SAXJ1808.4-3658 (Zhang, Yu & Zhang 1998, Stella et al. 2000). There are difficulties in recognition of stars at the propeller stage because of their faintness.

Stars-propellers escape apparent identification and may appear unusual. So, the whole class of cataclysmic variables (CVs) of nova-like type and particularly that of SW Sex type, having some anomalies, have been suggested by Horne (1999) as stars with disk-anchored propellers. But the only reliable example of the propeller is fascinating AE Aqr (Wynn, King & Horne 1997), where the rapidly spinning magnetic white dwarf (WD) operates as a propeller. Possibly, propellers work in the striking symbiotic stars (SSs) CH Cyg and MWC 560 too. The propeller in CH Cyg was suggested long ago (Mikolajewski & Mikolajewska 1988), but this is out of view of theorists until, in spite of scarcity of data on propellers. There are other SSs similar in some respects to CH Cyg and MWC 560. Therefore a magnetic propeller may be an widespread phenomenon amongst SSs. Here we study the observation appearances of a propeller by the examples of CH Cyg and MWC 560.

In Sect. 3 we discuss the observational properties of CH Cyg and MWC 560 in a framework of the magnetic propeller model, outlined in Sect. 2. The knowledge of observational signs of a propeller would allow it to be discriminated one amongst another object and we summarize them in Sect. 4.

2. A propeller model

A magnetic propeller model has been discussed in details everywhere (Lipunov 1992 and references therein). We use one of the variants of the model.

Let a WD of radius $R_s$ has a surface dipolar magnetic field $B_s$ and a rotation period $P_s$. The gas captured gravitationally by the WD settles on the star magnetosphere. Below the magnetosphere boundary the infalling gas is controlled by the magnetic field and corotates with the star. The gas accretes onto the surface of the star when the magnetosphere radius $R_m$ is smaller than the corotation radius, at which the keplerian velocity equals the velocity of corotation with the star, $R_{\text{cor}} = \left( \frac{GM_s}{\omega_s^2} \right)^{1/3}$, where $G$ is the gravitation constant, $M_s$ mass of the WD and $\omega_s = 2\pi/P_s$ its angular velocity. The accretion occurs because the gravitational acceleration dominates over the centrifugal acceleration. The reverse takes place...
and the infalling gas is expelled from the magnetosphere when \( R_m > R_{\text{cor}} \) — the rotating magnetic field acts as a propeller. Due to coexistence of the inflow and the outflow and hence their counteraction each other around the star-propeller, the accretion structure may be complex there. This is not well understood yet. It is expected that the expelled mass does not leave the star and the envelope builds up around the magnetosphere. In a steady state the magnetic pressure \( p_m \) at the upper boundary of the magnetosphere balances the gas pressure \( p_g \) just above this boundary:

\[
p_m = \frac{B^2}{8\pi} \left( \frac{R_x}{R_m} \right)^6 = p_g. \tag{1}
\]

While the mass accumulates, the envelope contracts the magnetosphere until the onset of the accretion phase \( (R_m < R_{\text{cor}}) \). The evolution of the envelope is connected with behavior of the magnetosphere and a simulation of this in comparison with the observations would give an insight into how a propeller operates.

The interaction between the envelope and rotating magnetic field of the star results in a development of a shear layer of width \( \delta \) comparable with the free fall length (Wang & Robertson 1985): \( \delta \sim \left( \frac{\rho_{\text{esc}}}{\rho_{R_m}} \right)^2 R_m \), where \( \rho_{\text{esc}} = \sqrt{2GM/R_m} \) is the escape velocity at \( R_m \), \( \eta \) in situ the effectiveness of damping of the convective motions in the shear layer by turbulent viscosity and is of order 1. This width is determined by convection, i.e. by the gravitation effect. In the subsonic case \( (\omega \rho R_m \lesssim \rho_c \) , which takes place when the magnetosphere radius is \( R_m \lesssim R_{\text{cor}} \), the form \( \delta \sim R_m \) is more appropriate for the shear layer width. The matter of the envelope penetrates into the shear layer via instabilities. The magnetic field mixes the matter and forces it to corotate. These processes determine the radius and state of the envelope.

In the shear layer the star-propeller transfers outside the angular moment and releases energy of rotation. The equality of the Alfvénic and the corotation velocities at the magnetosphere boundary, \( B^2/4\pi \rho = (\omega R_m)^2 \), is expected in a steady state on average (Wang & Robertson 1985). Then the energy release of the propeller is:

\[
L_p \sim \frac{B^2}{8\pi} P_x \times 4\pi R_m^2 \delta. \tag{2}
\]

### 3. Manifestations of the propeller in CH Cyg and MWC 560

CH Cyg and MWC 560 are symbiotic long-period binaries undergoing occasional 2 – 3 mag outbursts, as do classical SSs, but moreover showing a significant mass loss and jet ejection. Their hot continuum radiation originates in the envelope around the WD.

### Table 1: The binaries parameters.

|                  | CH Cyg | MWC 560 |
|------------------|--------|---------|
| \( \gamma \) (km s\(^{-1}\)) | 57.7   | 35      |
| \( K_g \) (km s\(^{-1}\))    | 4.9    | < 2     |
| \( \epsilon \)               | 0.47   | \( \approx \) 0.3 |
| \( M_x \) (M\(_{\odot}\))    | 3.5, M6 – 7 II | M4 – 5 III |
| \( M_g/M_{wd} \)             | 3.5    |         |
| \( P_{\text{orb}} \) (days)  | 5700   | 1930    |
| \( \omega_g \) (\(^\circ\))  | 142    |         |
| \( \nu_{\text{g}} \) (\(^\circ\)) | 90     | < 10    |
| \( a_{\text{orb}} \) (cm)    | 1.4 \(10^{14} \) | \( \approx \) 6 \(10^{13} \) |
| \( M_{\text{w}} \) (M\(_{\odot}\) y\(^{-1}\)) | \( \sim \) 10\(^{-7} \) | \( \sim \) 10\(^{-6} \) |
| \( V_{\text{w}} \) (km s\(^{-1}\)) | 30     |         |
| \( P_x \) (sec)              | 500    | 1320    |
| \( R_{\text{co}} \) (cm)     | 9.4 \(10^9 \) | < 2 \(10^{10} \) |
| \( V_{\text{eject}} \) (km s\(^{-1}\)) | 3000   | 7000    |

The envelope is observed in bright states, therefore it exists at least some years. The conventional models of symbiotic stars (Mikołajewska & Kenyon 1992) fail to account for activity in these stars and, in particular, for their high-velocity lumpy outflows and jets. The parameters of these binaries are given in Table 1.

### 3.1. CH Cyg

The semi-regular variable CH Cyg entered in period of activity in 1963 after almost a century of its observations in quiescence (Fig. 1). The outbursts are characterized by appearance of a hot blue continuum, strong emission lines of HI, HeI, FeII and [FeII] and short time photometric variability (flickering), similar to that of CVs. In the outbursts coherent oscillations of light with periods of 500 and 2000 – 3000 sec were observed (Mikołajewska et al. 1990, Hoard 1993). The duration of the outbursts is from one to several years. The most spectacular phenomenon was a sudden drop of brightness in 1984 with simultaneous ejection of jets with a velocity of about 1000 km/s. Intriguingly, this resembles outbursts in X-ray transients ejecting jets but on much longer timescales. In the outbursts the kinematics and the ionization of the gas evidence a high inhomogeneity and a shock pumping of radiation of the envelope around the WD (Faraggiana & Hack 1971, Persic, Hack & Selvelli 1984). The simultaneous fall and outflow of gas are observed in the envelope. The temperature of the envelope changes in the course of an outburst in a range from 7000 to 15000 K (Mikołajewska, Selvelli & Hack 1988).

The activity of the compact companion in the binary CH Cyg is powered by gas accretion from the giant’s wind. With the adopted parameters of the binary orbit and wind, the accretion mass rate is

\[
\dot{M}_a = \dot{M}_{\text{capt}} = \frac{1}{4} \left( \frac{R_{\text{esc}}}{\nu_{\text{g}}} \right)^2 \dot{M}_w = \left( \frac{G M_{\odot}}{a_{\text{orb}}} \right)^2 \frac{\nu_{\text{g}}}{V_{\text{w}}} =
\]
5.7 $10^{-9}\, M_\odot\, y^{-1}$ on average throughout the orbital period. Then the luminosity due to accretion onto the WD surface is $L_a = \frac{G M_2 \dot{M}}{2 R_\infty} \approx 10\, L_\odot$. The optical and IUE data show that the hot component luminosity $L_h = 240 - 300\, L_\odot$ during the bright state in 1981 – 84, and that the luminosity changed by a factor of 3.2 during the transitions from low to bright state in 1981 and back in 1984 (Mikołajewski et al. 1990). On the other hand, in quiescence the luminosity of the hot component was below $1\, L_\odot$, that is much lower than the wind powered accretion luminosity. Fig. 2 demonstrates the orbital dependence of the luminosity of the accretion onto the WD surface in the case of a spherical accretion of the giant’s wind. Both, the extremal values and sudden changes of the luminosity of the hot component, as well as the jet ejection, are problematic in a simple accretion model. The problems become aggravated in connection with the quasi-periodic dips of brightness (of relatively short-time duration, $\sim 3$ months), which were interpreted by Skopal et al. (1996) as eclipses in a triple system, and with the ejection of clumps with velocities up to 2500 km/s visible at least in the orbital plane (Tomov et al. 1996).

In the triple system the outbursts could be caused by episodic enhanced stripping of the giant at eccentric 756$^\circ$ orbit of the interior binary with following energetic accretion of the matter by the compact companion at the outer orbit. However the quasi-periodic dips could not be explained as eclipses in the triple system (Mikkola & Tanikawa 1998). Alternatively, the outbursts could be due to instability of the accretion disk like that of dwarf novae or X-ray transients. However, there is no reliable evidence of an accretion disk in CH Cyg. Although the propeller is able to put falling matter. In this case matter necessary for the forthcoming outburst may be stored in a thick envelope, supported against the gravitation by the propeller. Such an envelope will be lumpy and with a flat distribution of density. When enough mass will be accumulated, the envelope contracts the magnetosphere under the corotation radius and accretion onto the star surface will follow, that is the accretion phase. In the transition between the propeller and accretion phases, through the corotation radius, the envelope structure and the hot component luminosity will abruptly change. The sudden increase from 75 $L_\odot$ to 240 $L_\odot$ in the hot component luminosity in 1981 was probably such a catastrophic transition. Therefore we suppose the maximum propeller luminosity (when $R_m = R_{cor}$) is $L_p = 75\, L_\odot$ (the share of release of the gravitation energy of the gas falling onto the magnetosphere of the corotation radius $\sim 10^{10}\, \text{cm}$, for a star’s spin period $P_x = 500\, \text{s}$, is insignificant: $L_a \approx 0.5\, L_\odot$).

In the steady state on average properties of a propeller are determined by the position of magnetosphere relative to the corotation radius. The magnetosphere radius is approximately determined by the competition between the magnetic field pressure and gas pressure. In the case of $p_g = p_B = \frac{M_{\text{born}} (2 G M_x)^{1/2}}{4 \pi R_m^{3}}$ the field strength will be of order $B_a \sim 10^7\, \text{G}$ (from Eq. 4). However in the case of the envelope around the magnetosphere the idealization of free fall does not work and it is necessary to calculate self-consistently the interaction of the envelope with the magnetosphere to find $p_g(R_m)$. 

Figure 1: The long-term light curve of CH Cyg in V band (from VSNET, http://www.kusastro.kyoto-u.ac.jp/vsnet).

Figure 2: CH Cyg model orbital dependences of the radial velocities of the WD (solid line), the capture mass rate (dotted line) and luminosity of the accretion onto the WD surface (dashed line). Compare these with the behaviour of observed U brightness (dots), which is scaled by expression $U' = -U/6 - 6.2$ to fit right axis.
In other way, the strength of the WD magnetic field can be derived from Eq. 2 for the maximum propeller luminosity, i.e. when $R_m = R_{\text{cor}}$:

$$B_s \sim 6 \times 10^7 \left( \frac{L_p (R_m = R_{\text{cor}})}{100 L_\odot} \right)^{1/2} \left( \frac{P_x}{10 \text{ min}} \right)^{3/2} \text{ G.} \quad (3)$$

This field is strong enough to be measured. This would be possible only in the case of absence of the envelope. However the hot blue spectrum is then overwhelmed by the giant, that makes difficult the polarization measurements.

In quiescence the hot component luminosity is lower than 1 $L_\odot$, while the accretion onto the WD surface from the giant’s wind would be more energetic (Fig. 2). In a framework of the propeller model this is suppressed. When the envelope is negligible the magnetosphere radius may be approximately estimated from the balance between the magnetic pressure at the upper boundary of the magnetosphere and dynamical pressure of free falling gas. Eliminating $R_{\text{m}}$ from Eqs. 2 and 3, we have a minimum luminosity of the hot component produced by the interaction of the rotating magnetic field with the wind:

$$L_p \sim \frac{\eta^2 R_{\text{cor}}^2 (8G M_x M_{\text{cap}}^2)^{6/7}}{(B_x R_x)^{10/7}} = 1.1 \eta^2 \left( \frac{M_{\text{cap}}}{10^{-8} M_\odot y^{-1}} \right)^{12/7} \left( \frac{10^7 \text{ G}}{B_s} \right)^{10/7} \approx 0.3 L_\odot. \quad (4)$$

This equation defines a field of possible values of $B_s$ and $M_{\text{w}}$. In Fig. 2 the permitted values lie above the line corresponding to the propeller luminosity 0.3 $L_\odot$, that equals the minimum hot component luminosity between outbursts (Murset et al. 1991), and to the parameters $\eta = 1$ and $M_{\text{cap}}/M_{\text{w}} = 0.06$. So, $B_s = 10^{-7} M_\odot y^{-1}$ the field must be $\gtrsim 1.5 \times 10^7$ G. This limit is in good agreement with the estimate of $B_s$ made above on the base of the catastrophic transition, which is evidence of consistency of the propeller model with the observed values of $L_h$, $P_x$, and $M_{\text{w}}$.

In a framework of the propeller model, the dips of brightness of CH Cyg may be caused by instability of the accretion structure around the magnetosphere, whose energy release strongly depends on radius: $L_p \propto R_m^6$ (Eq. 2). Possibly, the lumpy nebula around CH Cyg, that appeared after the notable dip in 1984, was also caused by the propeller action. And it is evident that the jet ejection was immediately connected with the catastrophic transition between the accretion and propeller phases, when coupling of the magnetic field and gas is most effective (then the Alfvén and corotation velocities are equal).

3.2. MWC 560

MWC 560 is similar to CH Cyg (Mikołajewski, Tomov & Mikołajewska 1997), but differs by the orbit inclination, which is close to 0°. Therefore, the approaching jet in MWC560 is observed in blue-shifted absorption lines and sometimes the receding jet is observed in red-shifted emission lines. The approaching jet developed a maximum velocity of about 7000 km s$^{-1}$ in the outburst in 1990 (Tomov, Kolev, Georgiev et al. 1990). It seems that the jets outflows are inherent more or less permanently in polar directions (see Fig. 3), at least from the first observation of the blue-shifted high-velocity absorptions in 1943 (Merrill & Burwell 1943). The gas temperature in the jets is 7000 – 8000 K. The blue hot continuum of MWC 560 cannot be fitted either by an accretion disk model or by a model of nuclear burning on the surface of the WD (Panferov, Fabrika & Tomov 1997). Moreover, these models cannot account for the powerful wind and jets. The hot component radiation originates in the photosphere of the slow ($\sim 100$ km s$^{-1}$) powerful ($10^{-6} M_\odot y^{-1}$) wind with $T \approx 20000$ K and a radius of $4 \times 10^{13}$ cm. The low-velocity absorption and emission lines form in this wind.

From the similarity of both stars the high-velocity permanent polar outflows probably may occur in CH Cyg too. But they might be visible only in outburst as this happened in the biggest outburst in 1984 (Taylor, Seaquist & Mattei 1986). The permanent jets suggest a permanent jet engine to exist in these stars independent of details of the accretion structure (is it an envelope, or an accretion disk, or a ring), which strongly supports a propeller as the engine.

MWC 560 is one of a few SSs having flickering. Mikołajewski et al. (1998) reported a huge amplitude flickering of 0.7 magnitude. In 1992 we observed a rare burst in the H$\beta$ line with an amplitude of 3 for half an hour, which resembles quasi-regular bursts in AE Aqr. Besides there are semicoherent 22 min variations (Dobrzycka, Kenyon & Milone 1996). The or-
bital inclination of MWC 560 close to 0° gives us a happy chance to be in the cone of the jet and UV radiation from the deep of the photosphere. This explains why the hot component radiation is more hard and variable in MWC 560 than in CH Cyg. Also, the correlation of the UV flux and the jet velocity (Fig. 4) may be due to the effect of variable optical thickness of the jet.

The observed luminosity of MWC 560 is much lower than the critical Eddington luminosity. Therefore the radiation mechanisms cannot account for the wind and the jets. We suppose that they are accelerated by a propeller action of the magnetic WD. Then the outburst in 1990 could correspond to the catastrophic transition of the propeller, which means that its luminosity was \( L_p \sim 10^3 L_\odot \) when \( R_m = R_{co} \).

From Eq. 3 this gives a magnetic field strength \( B_s \sim 6 \times 10^8 \) G for the supposed WD's spin period \( P_x = 22 \) min.

4. Summary

The propeller model implies a magnetic field of WD in CH Cyg and MWC 560 to be of order \( 10^8 \) G. Measurement of such fields in polarization observations would be a straight way to verify the model. However this seems to be a very involved problem: the star surface and the magnetosphere are hidden from the observer under the photosphere of the outflowing wind.

In this paper we suggest only a scheme of the propeller model. It is believed that gas outflows form around the propeller in some sectors, or nonstationary gas ejection occurs when accretion is replaced by outflow. In some propeller scenarios envelopes or disks may form round the magnetosphere. But to define specifically the picture of accretion and outflow has been impossible so far. So further investigations of the accretion structure in CH Cyg and MWC 560 are important.

Acknowledgements. This work was supported by the Polish KBN Research Grant 2P03D 019.17.

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Figure 4: Time variations of MWC 560 activity. There are shown velocity of Hβ line core, radiation fluxes in optics (dots) and in UV (crosses). The left axis — velocity in km s\(^{-1}\), the right — radiation flux in \(10^{-13} \text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1}\).
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