On the origin of orbital period change in WY Cancri: a genuine angular momentum loss?

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Abstract

WY Cancri is a short-period ($P = 0.829$ d) eclipsing RS Canum Venaticorum stars, and both components are late-type stars. Recently, observations provided by photometric observations and light time minima show that the orbital period of WY Cancri is experiencing a secular decrease at a rate of $\frac{dP}{dt} = -1.2 \times 10^{-7}$ d yr$^{-1}$. In this Letter, we attempt to investigate if the period change of WY Cancri can originate from the angular momentum loss. In calculation, we assume that this source has a high wind loss rate of $\sim 10^{-10}$ $M_\odot$ yr$^{-1}$. To account for the observation, magnetic braking demands a strong surface magnetic field of $\gtrsim 10000$ G like Ap/Bp stars. Furthermore, if this source may be surrounded by a circumbinary disk, and $6\%$ of the wind loss feeds the disk, tidal torque between the disk and the binary can offer the observed angular momentum loss rate. Such a strong magnetic field or an extremely high wind input fraction seem to be highly unlikely.

Key words: stars: binaries: close — stars: individual (WY Cancri) — stars: mass-loss — stars: magnetic fields — stars: evolution

1. Introduction

Angular momentum loss plays an important role during the evolution of close binaries. For example, orbital angular momentum loss mechanisms are the vital input physics in studying the evolution of binaries by the stellar evolution code. In narrow binaries with an orbital period of $P < 3$ hr, gravitational wave radiation is a dominant angular momentum loss mechanism (Kraft, Matthews & Greenstein 1962; Faulkner 1971). The evolution of relatively wide binaries ($P > 3$ hr) is mainly governed by magnetic braking, which is driven by the coupling between the stellar winds and the magnetic field (Verbunt & Zwaan 1981). The angular momentum loss rate by magnetic braking is related with the mass, radius, magnetic field, and angular momentum of the magnetically active star, and is a more complicated issue. Nowadays, there exist several empirical prescriptions such as the standard magnetic braking model (Rappaport et al. 1983) and the reduced magnetic braking model (Sills et al. 2000), and so on. It is significant to test various magnetic braking models by observational data.

Close binaries can be ideal probes in examining various magnetic braking models. It is successful for magnetic braking theory in explaining the period gap of cataclysmic variables (CVs). However, the contamination of the light curve caused by the accretion processes in CVs results in a tiny change rate of orbital periods ($P \sim 10^{-5} - 10^{-4}$ yr$^{-1}$). Therefore, non mass-transferring pre-CVs such as NN Serpentis may be credible candidates (Brinkworth et al. 2006; Chen 2009). In this Letter, we attempt to explore if the angular momentum loss can be responsible for the orbital period change of WY cancri, which originated from the catalog of Strassmeier et al. (1993).

WY Cancri is a member of short-period eclipsing RS Canum Venaticorum (RS CVn) stars, which defined by Hall (1976). As a single-lined spectroscopic binary, the spectrum types of two components are G5 V and approximately M2, respectively (Arévalo & Lázaro 1999). Employing the optical photometry of WY Cancri, the system parameters have been derived (the detailed parameters see also Table 1, Zeitlik et al. 1990; Heckert et al. 1998). This source is a typical detached binary, and orbital period $P = 0.829$ d. By photometric observations and light time minima, it is discovered that the orbital period of this source is continuously decreasing at a rate of $\dot{P} = -1.44 \times 10^{-8}$ d yr$^{-1}$ (Hall & Kreiner 1980). Recently, by $O-C$ diagram analysis of WY Cancri Tian et al. (2009) reported that the orbital period is experiencing a secular decrease at a rate of $P = -1.2 \times 10^{-7}$ d yr$^{-1}$. Based on the period decrease rate caused by magnetic braking given by Guinan & Bradstreet (1988), Tian et al. (2009) obtained that the period change rate $\dot{P} = -4.5 \times 10^{-9}$ d yr$^{-1}$, which is very difficult to account for the observation. Therefore, it is an interesting work to explore the genuine origin of the secular period change of WY Cancri.

2. Analysis for angular momentum loss

2.1. Observed value

Considering a close binary with a circular orbit consisting of a primary star (of mass $M_1$), and a secondary star (of mass $M_2$), its orbital evolution is governed by
above, equation (1) yields
\[ \frac{\dot{J}}{J} = \frac{\dot{P}}{3P} + \frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2} - \frac{\dot{M}_T}{3M_T}, \]  
(1)
where \( \dot{J} = 2\pi a^2 M_1 M_2 / (M_T P) \) is the total orbital angular momentum of the binary, \( a = (GM_T P^2 / 4\pi^2)^{1/3} \) is the binary separation, \( G \) is the gravitational constant, \( M_T \) is the total mass of the binary.

The primary of WY Cancri is a solar-like star, which has a stellar wind loss-rate of \( 10^{-14} - 10^{-10} \, M_\odot \, yr^{-1} \), which depend on the stellar rotation rate (see also Wood et al. 2002). The mass-loss rates of several active M dwarf stars were estimated to be \( \sim 10^{-10} \, M_\odot \, yr^{-1} \) (Mullan et al. 1992). However, subsequent works presented contradictory results, which are 2 - 5 orders of magnitude lower than the one derived by Mullan et al. (1992) (Lim & White 1996; van den Oord & Doyle 1997; Wood et al. 2001; Wargelin & Drake 2002). Recently, employing 3D magnetohydrodynamical numerical simulations Vidotto et al. (2011) found that the mass-loss rates of M dwarf V374 Peg are \( 4 \times 10^{-10} \, M_\odot \, yr^{-1} \). Therefore, \( \dot{M}_1 / M_1, \dot{M}_2 / M_2, \) and \( \dot{M}_T / M_T \) are at least 2 - 3 orders of magnitude smaller than \( \dot{P} / P = -1.45 \times 10^{-7} \, yr^{-1} \). By the analysis mentioned above, equation (1) yields
\[ \frac{\dot{J}}{J} = \frac{\dot{P}}{3P} J. \]  
(2)
Adopting the observed data derived by Heckert et al. (1998) and Tian et al. (2009), the angular momentum loss rate of WY Cancri is
\[ \dot{J} = -4.3 \times 10^{36} \, g \, cm^2 \, s^{-2}. \]  
(3)

2.2. Magnetic braking

Both mass exchange and angular momentum loss can be responsible for the secular decrease in the orbital period of the binaries. When the material is transferred from the more massive primary to the less massive secondary, the orbital period continuously decreases. However, WY Cancri is a typical detached binary that has no mass exchange. Therefore, the angular momentum loss due to magnetic braking may lead to the period change of this source.

2.2.1. Standard magnetic braking model

Some works studied the solar wind loss and the rotational rates of solar-type stars in open clusters, and yielded the standard magnetic braking model (Weber & Davis 1967; Skumanich 1972; Mestel & Spruit 1987). The loss rate of angular momentum given by Rappaport et al. (1983) can be written as
\[ \dot{J}_{amb} \approx -3.8 \times 10^{-30} M R \omega^4 \, g \, cm^2 \, s^{-2}, \]  
(4)
where \( M, R, \omega \) are the mass, the radius, and the angular velocity of the magnetically active stars, respectively; \( \gamma = 0 - 4 \) is a dimensionless parameter. For WY Cancri, when \( \gamma = 0 \), we can calculate the angular momentum loss rate as
\[ \dot{J}_{amb} \approx -9.0 \times 10^{34} g \, cm^2 \, s^{-2}, \]  
(5)
which is 2 orders of magnitude smaller than the observed result given by equation (3).

2.2.2. Analytical magnetic braking model

To account for the formation of black-hole low-mass X-ray binaries with a short orbital-period (\( P < 1 \, d \)), Justham et al. (2006) proposed an anomalous magnetic braking mechanism of Ap/Bp stars. In their work, an analytical magnetic braking description is given by
\[ \dot{J}_{amb} = \frac{2\pi}{P} (GM)^{-1/4} B_s R^{13/4} M_{wind}^{1/2}, \]  
(6)
where \( B_s, M_{wind} \) are the surface magnetic field, and the stellar wind loss rates of the magnetically active stars, respectively.

Inserting the observed parameters of WY Cancri, surface magnetic field of 10000 G, and stellar wind loss rates of \( 10^{-10} \, M_\odot \, yr^{-1} \), equation (6) yields
\[ \dot{J}_{amb} = -2.96 \times 10^{36} \left( \frac{0.829 d}{P} \right) \left( \frac{0.81 M_\odot}{M} \right)^{1/4} \left( \frac{B_s}{10000G} \right) \left( \frac{R}{0.93 R_\odot} \right)^{13/4} \left( \frac{M_{wind}}{10^{-10} M_\odot \, yr^{-1}} \right)^{1/2} \, g \, cm^2 \, s^{-2}. \]  
(7)

In Figure 1, we plot the calculated angular momentum loss rate as a function of the primary’s surface magnetic field. It is clearly seen that, if the primary of WY Cancri has a strong magnetic field of \( \gtrsim 10000 \, G \) like Ap/Bp stars (Moss 1989; Braithwaite & Spruit 2004), magnetic braking can interpret the period change of this source.

2.3. Circumbinary disk

In fact, there may exist other efficient mechanism extracting angular momentum from the binary such as circumbinary (CB) disk (Chen et al. 2006). CB disk may originate from a slow wind near the orbital plane forming by the lost material during the mass transferring of binary systems (van den Heuvel & de Loore 1973; van den Heuvel 1994), or the remnant of common envelope (CE) that cannot be entirely ejected during CE phase (Spruit & Taam 2001). The tidal torques induced by the gravitational interaction between the inner edge \( r_i \) of the CB disk and the binaries can efficiently extract the orbital angular momentum from the binary systems.

| Zeilik et al. (1990) | Heckert et al. (1998) |
|---------------------|----------------------|
| primary mass | 0.82 M_\odot | 0.81 M_\odot |
| primary radius | 0.94 R_\odot | 0.93 R_\odot |
| secondary mass | 0.31 M_\odot | 0.31 M_\odot |
| secondary radius | 0.59 R_\odot | 0.58 R_\odot |
| mass ratio | 0.356 ± 0.176 | 0.384 ± 0.009 |
If WY Cancri is surrounded by a CB disk, and a fraction \( \delta \) of the stellar wind from the primary feeds into the CB disk, Spruit & Taam (2001) and Taam & Spruit (2001) deduced the following angular momentum loss rate

\[
\dot{J}_{cb} = -\gamma \left( \frac{2\pi a^2}{P} \right) \delta M_{\text{wind}} \left( \frac{t}{t_{vi}} \right)^{1/2}, \tag{8}
\]

where \( \gamma = \sqrt{r_i/a} \) is a dimensionless parameter, \( t \) is the timescale of the stellar wind feeding the CB disk. Assuming that the CB disk abides by the standard \( \alpha \) prescription (Shakura & Sunyaev 1973), the viscous timescale at the inner edge of the disk \( t_{vi} = 2\gamma^3 P/(3\pi\alpha_{SS} \beta^2) \), where \( \alpha_{SS} \) and \( \beta \) are the viscosity parameter, and the dimensionless parameter described the scale height at \( r_i \) of the CB disk, respectively.

For WY Cancri, the binary separation \( a = 2.68 \times 10^{11} \text{ cm} = 3.85 \text{ R}_\odot \). Taking the typical parameters \( \gamma = 1.3, \alpha_{SS} = 0.01, \beta = 0.03 \) (Chen et al. 2006), then the viscous timescale \( t_{vi} = 118 \text{ yr} \). We will adopt an extremely high stellar wind loss rate of \( \sim 10^{-16} M_\odot \text{ yr}^{-1} \), and also assume that phase during which the wind has been that extreme has lasted for about 0.2 Gyr (see also Wood et al. 2002). Using the above parameters, equation (8) yields

\[
\dot{J}_{cb} = -3.4 \times 10^{36} \left( \frac{P}{0.829 \text{ d}} \right)^{-1} \left( \frac{a}{3.85 R_\odot} \right)^2 \left( \frac{\delta}{0.05} \right) \left( \frac{M_{\text{wind}}}{10^{-10} M_\odot \text{ yr}^{-1}} \right) \left( \frac{t}{0.2 \text{ Gyr}} \right) \left( \frac{118 \text{ yr}}{t_{vi}} \right)^{1/2} \text{ g cm}^2 \text{ s}^{-2}. \tag{9}
\]

Figure 2 shows angular momentum loss rate calculated by a CB disk as a function of the wind feeding fraction \( \delta \). As shown in this figure, for a high wind feeding fraction of 0.06 \(^1\), the CB disk can be responsible for the orbit decay of WY Cancri.

3. Summary and Discussion

In this Letter, we have tested if the angular momentum loss can be responsible for the secular period change of WY Cancri. Our main results are summarized as follows.  
1. The period change of WY Cancri cannot be explained by the standard magnetic braking model, in which the angular momentum loss rate is 2 orders of magnitude lower than the observed value.
2. If the primary of WY Cancri has a strong magnetic field \( \gtrsim 10000 \text{ G} \), and a high wind loss rate of \( \sim 10^{-10} M_\odot \text{ yr}^{-1} \), magnetic braking description given by analytical method can account for the observation. Although the magnetic activity of RS CVn stars is drastic (Donati et al. 1995; Osten & Brown 1999; Kochukhov et al. 2013), such a high magnetic field is still unfrequent. We expect that Zeeman Doppler imaging method in this source can constrain the surface magnetic field, and confirm or negate magnetic braking mechanism.
3. If this source is enclosed by a CB disk, and assuming that 6% of the stellar wind loss rate of \( \sim 10^{-10} M_\odot \text{ yr}^{-1} \) feeds the disk, the corresponding loss rate of angular momentum can interpret the observed value. The mass of CB disk can be estimated to be \( \sim 10^{-3} M_\odot \), which is significantly higher than the inferred value (\( \sim 10^{-9} M_\odot \)) given by Muno & Mauerhan (2006). Therefore, such an extremely high wind input fraction seem to be highly unlikely.

If the period decrease recently observed in WY Cancri is indeed a secular phenomenon, a genuine angular momentum loss should be employed. In an allowable parameters

\(^1\) This wind input fraction would be 1 - 2 orders of magnitude higher than that adopted by Spruit & Taam (2001).
range, magnetic braking or CB disk may be responsible for the orbit decay of WY Cancri. Of course, the observed period decrease may also be a short-term phenomenon, and is only a stage of long-period oscillation (Tian et al. 2009). If so, Applegate’s mechanism (which also requires a strong magnetic field of \( \sim 1000 \) G, Applegate 1992), or the presence of a third body in a long orbit around the binary may be responsible for the period decrease. Therefore, long-term observation in multiwaveband for WY Cancri should be continuously in progress in the future.

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