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A MECHANISM FOR ORBITAL PERIOD MODULATION AND IRREGULAR ORBITAL PERIOD VARIATIONS IN CLOSE BINARIES

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ABSTRACT

Orbital period modulation is observed in many magnetically active close binaries. It can be explained by magnetic connection between two stars. Magnetic connection produces weak force between the two stars. As the magnetic field varies periodically, the orbital period also shows cyclical variations. The mechanism can also be used to explain irregular orbital period variations and orbital period jumps. The mean surface magnetic strength is calculated by using the Radia package, which is dedicated to 3D magnetostatics computation. On the basis of the results, a practical equation is given to calculate surface magnetic strength.

Subject headings: binaries: close — stars: activity — stars: magnetic fields

1. INTRODUCTION

Orbital period modulation often appears in Algol, RS Canum Venaticorum, W Ursae Majoris systems, and cataclysmic variables with relative amplitudes of $\Delta P/P \sim 10^{-7}$ to 10^{-5}. Irregular orbital period variations and orbital period jumps are also prevalent in close binaries, such as AR Lac (see Siviero et al. 2006, Fig. 3), TW Dra (see Qian & Boonrucksar 2002, Fig. 1), TU Her (see Qian 2000, Fig. 4), and RW Tau (see Šimon 1997a, Fig. 1).

Light-time effect is often used to explain the orbital period modulation. However, in most cases a third body with large mass is absent in its spectrum. Moreover, many observations indicate the orbital period variations are quasi-periodic or irregular, but the light-time effect requires that period variations be strictly periodic. Applegate (1992) proposed a model in which redistribution of angular momentum in the magnetically active components causes variations in the oblateness of the star, and therefore produces gravity changes and orbital period variations. But, Lanza (2005, 2006) found that the necessary energy to drive angular momentum exchanges between the inner and outer convective shells is much more than that supplied by the stellar luminosity. In this Letter, we present a mechanism involving magnetic connection to explain orbital period modulation and irregular orbital period variations including orbital period jumps.

2. MAGNETIC CONNECTION MODEL

As the components in binary systems rotate about 10–100 times faster than the Sun does, the magnetic field is expected to be much stronger than that of the Sun. In addition, the binary separation is very small with $a/(R_1 + R_2) \sim 1$–3, where a is the separation and R_1 and R_2 are the radii of the two components, respectively. With such a small separation, the magnetic fields of the two components encounter each other and connect. Then, the two stars will magnetize each other. So, it is reasonable to suppose that the magnetic axes of the two components will move in the line connecting the stars' centers. On the basis of these assumptions, we develop a simplified magnetic connection model to explain orbital period modulation and irregular period variations.

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The gravitational force between the two components is

$$F_g = a\omega^2 M_\mu = a\left(\frac{2\pi}{P}\right)^2 M_\mu, \tag{1}$$

where $M_\mu = M_1M_2/(M_1 + M_2)$, and ω and P are angular velocity and orbital period, respectively. Differentiating equation (1) and using Kepler's third law, we obtain

$$\frac{\Delta F_g}{F_g} = -\frac{4}{3}\frac{\Delta P}{P}. \tag{2}$$

In order to produce the variation amplitude $\Delta P/P$, the required variation in magnetic force ΔF_m must satisfy

$$\Delta F_m = -\frac{4}{3}\frac{\Delta P}{P}F_g = -\frac{4}{3}\frac{\Delta P}{P}\frac{GM_1M_2}{a^2}, \tag{3}$$

where G is the gravitational constant, and M_1 and M_2 are the masses of the two components.

A reference frame with its origin at the barycenter of the primary star and the z-axis in the line connecting the stars' centers is assumed to corotate with the system. A spherical polar coordinate system (r, θ, φ) is used, where r is the distance from the origin, θ is the colatitude measured from 0° at the $+z$-axis (or the second component) to 180° at the $-z$-axis, and φ is the longitude measured counterclockwise from 0° to 360°. For simplicity, we assume that the magnetic field inside the two stars, B_0, is uniform and identical, and along the $+z$-axis. The two components can be taken as two magnetic dipoles with magnetic moment given by

$$\boldsymbol{m}_{1,2} = \frac{4\pi R_{1,2}^3}{3}\frac{B_0}{\mu_0}\boldsymbol{e}_z, \tag{4}$$

where μ_0 is the magnetic conductivity constant in a vacuum. The magnetic scalar potential produced by the primary component star at r is

$$\psi(\boldsymbol{r}) = \frac{\boldsymbol{m}_1 \cdot \boldsymbol{r}}{4\pi r^3} = \frac{m_1 cos\theta}{4\pi r^2}. \tag{5}$$

TABLE 1
THE BASIC PARAMETERS AND REQUIRED MAGNETIC FIELD FOR SOME CLOSE BINARIES THAT SHOW ORBITAL PERIOD VARIATIONS

Name	Type	M_1 ($M_\odot$)	R_1 ($R_\odot$)	M_2 ($M_\odot$)	R_2 ($R_\odot$)	a ($R_\odot$)	$\Delta P/P$ ($\times 10^{-6}$)	ΔF ($\times 10^{25}$ N)	B_0 (T)	$\overline{B}_s$ (T)	Reference
RT LMi	EW	1.28	1.28	0.48	0.83	2.64	3.1	19.9	23.9	2.0	1
EQ Tau	EW	1.23	1.14	0.54	0.79	2.48	4.6	36.1	34.5	2.7	2
TY Boo	EW	1.14	1.05	0.53	0.75	2.32	6.9	56.3	45.4	3.7	3, 4
FG Hya	EW	1.44	1.41	0.161	0.59	2.34	13.6	41.8	52.4	4.2	5
XY Leo	EW	0.46	0.66	0.76	0.83	1.95	21.3	142.3	80.5	6.4	6
SV Cam	EB	0.86	0.98	0.65	1.18	3.41	3.0	10.5	47.0	3.7	1, 7
ZZ Aur	EB	1.62	1.73	0.76	1.26	4.0	3.5	19.6	25.3	2.1	8
DI Peg	EB	1.18	1.41	0.70	1.37	4.14	3.0	10.5	29.1	2.3	9
CG Cyg	EA	0.97	1.00	0.80	0.83	3.7	2.4	9.9	136.0	10.9	10, 11
RT Lac	EA	1.58	4.25	0.62	4.80	15.8	8.4	2.4	9.0	0.7	12, 13
RT CrB	EA	1.34	2.61	1.36	2.95	17.4	5.4	2.4	61.6	4.9	14, 15
AR Lac[a]	EA	1.21	2.61	1.17	1.51	8.87	24.0	31.4	143.0	11.4	16
TW Dra[a]	EA	1.7	2.4	0.8	3.4	11.4	91.6[b]	69.7	110.0	8.8	17, 18
TU Her[a]	EA	1.54	1.56	0.46	2.46	9.14	28.2	17.4	119.8	9.6	19, 20
RW Tau[a]	EA	2.43	2.97	0.55	4.45	15.8	16.1	6.3	32.3	2.6	21, 22

[a] These show irregular orbital period variations.
[b] Calculated by the present authors.

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The magnetic field at $\boldsymbol{r}$ is

$$\boldsymbol{B} = -\mu_0 \boldsymbol{\nabla}\psi(\boldsymbol{r}) = \frac{\mu_0 m_1}{4\pi r^3}(2\cos\theta \boldsymbol{e}_r + \sin\theta \boldsymbol{e}_\theta), \tag{6}$$

where $\boldsymbol{e}_r$ is unit vector in the r-direction and $\boldsymbol{e}_\theta$ is unit vector in the θ-direction. Using equation (4), the force on the other magnetic dipole (the second component) at $\boldsymbol{r} = a\boldsymbol{e}_z$ is

$$\boldsymbol{F}_m = (\boldsymbol{m}_2 \cdot \boldsymbol{\nabla})\boldsymbol{B} = -\frac{3\mu_0 m_1 m_2}{2\pi a^4}\boldsymbol{e}_z = -\frac{8\pi B_0^2 R_1^3 R_2^3}{3\mu_0 a^4}\boldsymbol{e}_z. \tag{7}$$

Given that $0 \leq \Delta B \leq 2B_0$ ($\Delta B = 2B_0$ if the magnetic axis reverses just as the Sun does every 11 years), we assume $\Delta B \sim B_0$ and $\Delta F_m \sim F_m$. Then combining equations (3) and (7) gives

$$B_0 \sim a\left(\frac{\mu_0 G}{2\pi}\frac{M_1 M_2}{R_1^3 R_2^3}\frac{\Delta P}{P}\right)^{1/2} = 1.5 \times 10^4 a\left(\frac{M_1 M_2}{R_1^3 R_2^3}\frac{\Delta P}{P}\right)^{1/2} \ \mathrm{T}, \tag{8}$$

where $M_{1,2}$, $R_{1,2}$, and a are in solar units and P is in days.

Equation (7) indicates that the magnetic force is sensitive to a. However, the face-to-face separation between the two components is much smaller than the center-to-center separation, a. In order to get an accurate estimate of the magnetic force, we use the Radia[3] software package to calculate the magnetic force between the two components. First, we take two stars as two cylindric magnets with magnetic and geometrical axes both along the line connecting the stars' centers. The magnetic axes do not move relative to the stars as the binary system rotates synchronously. We assume the cylindric magnets with heights of $2.0R_{1,2}$ and radii of $0.4R_{1,2}$. The magnets are magnetized uniformly with B_0. As the genuine radius in the direction of the line connecting the stars' centers is larger than R_1 or R_2, we move the two cylindric magnets a little closer. For a contact binary (EW-type binary), the face-to-face separation is zero, so we placed the two magnets so that they are touching. For a near-contact binary (EB-type binary), we move the two magnets closer by $0.2(R_1 + R_2)$. For a detached or semidetached binary (EA-type binary), we move the two magnets closer by $0.1(R_1 + R_2)$.

In order to produce the magnetic force given by equation (3), the required magnetic field B_0 is calculated for several close binaries which show orbital period variations, and listed in Table 1, along with other relevant parameters. In fact, the magnetic fields of the two stars are superposed. What is given in Table 1 is the superposed field.

The total magnetic flux that passes beyond one cylindric magnet is given by $\Phi = \pi(0.4R_{1,2})^2 B_0$. We assume that the magnetic flux, Φ, passes uniformly through the stellar hemisphere which faces away from the other star (see Fig. 1). So, the mean magnetic field on the hemisphere is $\overline{B}_s = \Phi/(2\pi R_{1,2}^2) = 0.08B_0$. Our calculation shows the magnetic strength in the space between the two stars is $\sim(2\text{–}6)\overline{B}_s$. However, the magnetic field in the space cannot be observed by us. So $\overline{B}_s$ is used as the mean magnetic field that we can observe.

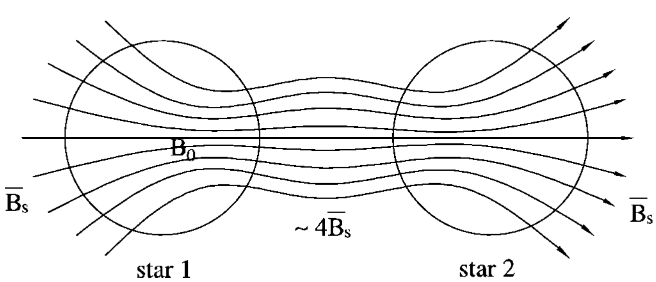

FIG. 1.—Possible configuration of the magnetic field in a close binary system.

[3] The Radia package is developed by European Synchrotron Radiation Facility and is available at http://www.esrf.eu/Accelerators/Groups/InsertionDevices/Software/Radia/Radia_download.

Using the results calculated with the Radia package, $\overline{B}_s$ can be expressed in the form of equation (8):

$$\overline{B}_s = ka \left(\frac{M_1 M_2}{R_1^3 R_2^3} \frac{\Delta P}{P}\right)^{1/2} \text{ T}, \tag{9}$$

where $k \sim (0.5\text{–}0.8) \times 10^3$ for contact binaries, $k \sim (0.8\text{–}1.1) \times 10^3$ for near-contact binaries, and $k \sim (1.2\text{–}1.8) \times 10^3$ for semidetached and detached binaries. $M_{1,2}$, $R_{1,2}$, and a are in solar units and P is in days. This equation gives smaller $\overline{B}_s$ than equation (8) by an order of magnitude.

3. DISCUSSION AND CONCLUSIONS

A mechanism of magnetic connection has been introduced to explain orbital period modulation and irregular orbital variations, especially, a small amplitude of orbital period variations. For some systems, a small amplitude of quasi-periodic or irregular orbital period variations is superposed on an increasing, decreasing, or cyclically varying orbital period. These small variation components can also be explained very well by our model, as the required magnetic field is weak according to equation (9).

Helioseismology reveals that the poloidal magnetic field in the solar core can become as intense as ∼200 T (Rashba et al. 2007). This field is consistent with the B_0 in our model. If the internal magnetic field in one component rises up along the line connecting the stars' centers under buoyancy force and magnetic traction of the other component, a strong magnetic field will appear in the space between the two stars.

Our computation indicates that the mean surface magnetic strength required for period variations is 1–10 T. If the magnetic axes are not along the line connecting the stars' centers, the required magnetic field on the surface which can be observed will increase by 10%–100%. It is well known that the bigger the sunspot, the stronger the magnetic field. Spots in binary systems are 100–1000 times bigger than sunspots. So, the spot magnetic field in binary systems is expected to be much stronger than the sunspot magnetic field (∼0.25 T), suggesting that the mean surface field, $\overline{B}_s$, may be in agreement with our predictions. Zeeman observations of the Hα region indicate that a magnetic field of ∼4 T exists on the magnetically active binary star BY Dra (Anderson et al. 1976), which is in general consistent with the required magnetic field of 5–6 T if the typical $\Delta P/P$ of 10^{-6} and the basic parameters given by Boden & Lane (2001) are adopted.

According to our model, the quasi-periodic/irregular orbital period changes are accompanied by variations in magnetic activity, which is reflected by Hα emission, Ca II H and K emission, and so on. Hall (1991) and Šimon (1997b) found that changes of the orbital periods of CG Cyg and U Sge are correlated with the brightness variations. This is compatible with our model. In order to further verify our theory, long-term observations of magnetic fields and chromospheric activity are needed for eclipsing close binaries.

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