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Orbital period changes of the W UMa binary YY Eri

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Abstract Orbital period changes of the W UMa-type binary YY Eri are analyzed by using all photoelectric and ccd times of light minimum. The results show that its orbital period is undergoing a secular increase superposed on two cyclic oscillations. The continuous increase at the rate of $dP/dt = 6.3806 \times 10^{-8}$ d yr^{-1} may be accounted for by mass transfer from the less massive companion to the more massive one. Two periodic variations with periods of 38.6192 and 22.3573 yr may be attributed to the light-time effect of a faint third star and the cyclic magnetic activity of the system, respectively.

Key words: stars: binaries: close — stars: binaries: eclipsing — stars: individual (YY Eri)

1 INTRODUCTION

YY Eridani (YY Eri, AN 169.1932, HD 26609, BD $-10.858°$) is a W UMa-type binary. It first appeared as a new variable in a list compiled by Hoffmeister (1933), who classified it as a short period eclipsing binary with a spectral type of G5. Jensch (1934) observed this system photographically and visually, and obtained a linear ephemeris with an orbital period of $0.321496\,$d. Lause (1937) reported a light curve with a flat-topped maximum. Bodokia (1938) made photographic observations and found that YY Eri is a W UMa-type binary system. Spectroscopic observations were first performed by Struve (1947), where YY Eri was further determined to be a W-subtype binary and the spectral type of both its components is about G5. First photoelectric observations in blue and yellow bands were carried out by Cillié (1951). He found that the light curves showed two equal maxima and no flat portion. Subsequently, a number of researchers (Huruhata et al. 1953; Binnendijk 1965; Maceroni et al. 1982; Eaton 1986; Nesci et al. 1986; Muyesseroglu et al. 1990; Maceroni et al. 1994; Budding et al. 1996; Yang & Liu 1999; Duerbeck & Rucinski 2007) performed both photometric and spectroscopic studies, and gradually determined the physical parameters of the binary system. Huruhata et al. (1953) analyzed their own data and data from Struve (1947), and obtained a spectroscopic mass ratio of $q \simeq 0.59$. Combining the photoelectric observations of Purgathofer & Purgathofer (1960) with the spectroscopic data of Struve (1947), Binnendijk (1965) derived some absolute elements. With the Wilson-Devinney code (Wilson & Devinney 1971), Maceroni et al. (1982) re-analyzed the data of Binnendijk (1965). They suggested that the temperature difference between its two components approaches $200\,$K, and the degree of overcontact $f \simeq 18\%$. Eaton (1986) published the VRI light curves, from which he obtained the mass ratio of $q \simeq 0.5$ and the inclination of $i = 80.8°$. Nesci et al. (1986) performed spectroscopic observations and derived the parameters of the system: $M_1 = 1.54\,M_\odot$, $M_2 = 0.62\,M_\odot$, $R_1 = 1.20\,R_\odot$ and $R_2 = 0.77\,R_\odot$. Moreover, they obtained a photometric solution with a mass ratio of $q = 0.401$, an inclination of $i = 82.5°$ and a degree of overcontact $f = 15\%$. Yang & Liu (1999) reported the complete BV light curves with an unequal quadrature light level, i.e., the well-known O'Connell effect (O'Connell 1951). Their photometric resolution suggested that this effect might originate from a cool spot on the primary star. Also, they confirmed that YY Eri is a W-subtype contact binary, and determined a mass ratio of $q = 0.4699$ and an inclination of $i = 82.12°$. Duerbeck & Rucinski (2007) measured the radial velocities. They determined a spectral type of about G3V and a spectroscopic mass ratio of $q \approx 0.44$.

Apart from light curve analyses, the orbital period change of YY Eri has been also intensively investigated by many authors (Jensch 1934; Bodokia 1938; Cillié 1951; Kwee 1958; Strauss 1976; Panchatsaram & Abhyankar 1981; Kim 1992; Maceroni & van't Veer 1994; Kim et al. 1997; Karube et al. 2000), and several distinct behaviors of period variations were reported, which are summarized in Table 1.

Firstly, a stable period was revealed in some earlier studies (Bodokia 1938; Cillié 1951; Kwee 1958). Subsequently, Strauss (1976) found that its orbital period exhibited a continuous increase. However, with the accumulation of observations, Panchatsaram & Abhyankar (1981) concluded that no period change occurred during the last 20 yr. Based on 35 photoelectric times of light minimum, Kim (1992) analyzed the period changes and found a sinusoidal trend in the $O-C$ diagram. Maceroni et al. (1994) added some new observations and found that these recent observations substantially deviated from the sinusoidal fit of Kim (1992). Later, Kim et al. (1997) reinvestigated the orbital period variations in detail based on all available times of light minimum at that time. Their results indicated that the orbital period of YY Eri was undergoing either a sinusoidal oscillation plus a secular period increase, or experienced five abrupt period jumps during past decades. However, in the study of Karube et al. (2000), only four abrupt period jumps were found. So far, an explicit orbital period change of YY Eri is still missing although the rich data of light-minimum times cover a wide interval. Fortunately, many new and regular observations during the last twenty years have been reported and provided an opportunity to further determine the period changes of YY Eri. In this paper, we have collected all photoelectric and CCD minima spread over 66 yr, from 1950 to 2016, and discuss mechanisms causing its period changes.

2 ORBITAL PERIOD VARIATIONS OF YY ERI

In order to build the $(O-C)$ diagram, we have performed a careful search for all photoelectric and ccd times of light minimum and collected 130 photoelectric minima and 150 ccd data. Among them, 235 data are taken from two well-known databases: the $(O-C)$ gateway[1] and the Lichtenknecker database of BAV[2], and 45 other data values were gathered from the literature and listed in Table 2. The $(O-C)$ values of the minima times were then calculated with the following linear ephemeris provided by Kreiner (2004)

$$\mathrm{Min.I} = 2441581.6229 + 0.321496855E. \qquad (1)$$

In the computation, the $(O-C)$ values in the same epoch are averaged. The corresponding $O-C$ diagram is shown in the upper panel of Figure 1. In addition, one photoelectric data point [HJD 2454373.3945 (Yilmaz et al. 2009)], marked by the symbol "×" in Figure 1, is not adopted for further analysis since it shows a large deviation from the general trend formed by all other $(O-C)$ data.

From the upper panel of Figure 1, one can note that the orbital period of YY Eri is variable and the variation is complex. Firstly, the $(O-C)$ diagram exhibits an upward parabolic trend, which indicates that the orbital period of YY Eri should be undergoing a continuous increase. Applying the least-squares method generates the following nonlinear ephemeris

$$\begin{aligned}\mathrm{Min.I} =& 2441581.6171(2) + 0.321496162(10)E \\ &+ 2.81(3)\times 10^{-11}E^2,\end{aligned} \qquad (2)$$

which is plotted as a dashed curve in Figure 1. During the fitting process, the primary and secondary eclipse times are not treated independently due to absence of possible apsidal motion and a reasonable assumption of a circular orbit for short period binaries (Zahn 1966, 1977). The corresponding quadratic term yields a continuous period increase at the rate of $dP/dt = 6.3806\times10^{-8}\,\mathrm{d\,yr^{-1}}$. After the continuous period increase is removed from the $(O-C)$ diagram, the residuals $(O-C)_1$, displayed in the middle panel of Figure 1, reveal a complex and periodic variation. By using PERIOD04 (Lenz 2004, Yang et al. 2012, Li et al. 2016), we performed a Fourier analysis on the $(O-C)_1$ residuals which is depicted in Figure 2. Two significant peaks in the power spectrum are somewhat close to each other and located at the frequencies of $f_1 = 7.2397\times10^{-5}\,\mathrm{d^{-1}}$ and $f_2 = 1.2204\times10^{-4}\,\mathrm{d^{-1}}$, respectively. Thus, two corresponding periods are estimated to be 37.8174 yr and 22.4340 yr. With a double-sine function to fit the $(O-C)_1$ residuals, the least-squares method generates the following equation

$$\begin{aligned}(O-C)_1 =& -0.0018(6) - 0.0065(3)\sin[0^\circ.0082(2)E \\ &- 50^\circ.9103(\pm2^\circ.8980)] \\ &- 0.0035(3)\sin[0^\circ.0142(3)E \\ &- 65^\circ.6335(\pm4^\circ.2786)].\end{aligned} \qquad (3)$$

[1] *http://var.astro.cz/ocgate/*
[2] *http://www.bav-astro.de/LkDB/index.php*

Table 1 Summary of the Orbital Period Changes in YY Eri from the Literature

Year	Revised period (d)	Continuous change (d yr^{-1})	Abrupt change (times)	Cyclic change Amplitude (d)	Period (yr)	Ref.
1934	0.321496	-	-	-	-	[1]
1938	0.321494	-	-	-	-	[2]
1951	0.32149510	-	-	-	-	[3]
1958	0.32149588	-	-	-	-	[4]
1976	0.321496212	4.0×10^{-8}	-	-	-	[5]
1981	0.32149588	-	-	-	-	[6]
1992	0.32149591	-	-	0.00336	24.24	[7]
1997	0.32149560	1.98×10^{-8}	-	0.0045	30.2	[8]
1997	0.32149560	-	5	-	-	[8]
2000	0.321496212	-	4	-	-	[9]

References: [1] Jensch (1934); [2] Bodokia (1938); [3] Cillié (1951); [4] Kwee (1958); [5] Strauss (1976); [6] Panchatsaram & Abhyankar (1981); [7] Kim (1992); [8] Kim et al. (1997); [9] Karube et al. (2000).

Two sinusoidal terms reveal two cyclic period variations with the periods of $P_{\rm mod1} = 38.6192\,$yr and $P_{\rm mod2} = 22.3573\,$yr, which are almost the same as the corresponding periods ($37.8174\,$yr and $22.4340\,$yr) derived from the power spectrum. A total fitting curve combining the upward parabola with two sinusoidal terms is displayed as the solid line in the upper panel of Figure 1. The final residuals are constructed in the lower panel of Figure 1. The quadratic sum of residuals is $\sum_i (O-C)_i^2 = 0.00087\,{\rm d}^2$. Although the final residuals display relatively large systematic variations, they do not indicate a clear and regular trend. Therefore, the above fits should be sufficient at this time.

3 DISCUSSIONS AND CONCLUSIONS

The above analyses suggest that the orbital period variations of YY Eri show a relatively complex pattern where a long-term period increase and two periodic oscillations are concomitant. In general, the secular period increase can be interpreted as a result of mass transfer from the less massive star to the more massive one. If the total mass is considered to be conservative, the mass-transfer rate can be estimated according to the following equation derived by Pringle (1975),

$$\dot{M}_2 = -\dot{M}_1 = -\frac{2\gamma}{3P^2}\frac{M_1 M_2}{M_1 - M_2}, \qquad (4)$$

where $\gamma = 2.8082 \times 10^{-11}$ is the coefficient of E^2 in Equation (2) and $P = 0.321496379\,$d is the orbital period of the binary. By inserting the physical parameters $M_1 = 1.54\,M_\odot$ and $M_2 = 0.62\,M_\odot$ (Nesci et al. 1986) into Equation (4), the mass-transfer rate is calculated as $\dot{M}_2 = -6.8658 \times 10^{-8}\,M_\odot\,{\rm yr}^{-1}$. If the donor (secondary) star transfers its mass to the acceptor (primary) star on a Kelvin-Helmholtz (i.e. thermal) timescale defined as $\tau_{\rm th} = \frac{GM_{\rm d}^2}{R_{\rm d}L_{\rm d}}$ (Paczyński 1971), the thermal timescale $\tau_{\rm th} = 2.9416 \times 10^7\,$yr may be estimated and a mass-transfer rate on a thermal timescale is then roughly calculated as $\frac{M_2}{\tau_{\rm th}} = 2.1077 \times 10^{-8}\,M_\odot\,{\rm yr}^{-1}$. Clearly, the mass-transfer rate estimated from the thermal timescale is smaller than that inferred from Equation (4), which indicates that conservative mass transfer from the secondary to the primary star can be enough to cause the observed period increase.

In theory, the continuous mass transfer of YY Eri could generate a persistent hot spot on the surface of the primary star. Moreover, this hot spot would move due to the Coriolis force, so that it might be detected near phase 0.25. However, the photometric solutions provided by Eaton (1986) and Muyesseroglu et al. (1990) did not suggest that such hot spot is just on the primary. Perhaps, the real situation might be more intricate since some cool spots could exist on the binary (Yang & Liu 1999). Also, such complication has been presented by the analyses of both its light curves and spectroscopic Doppler imaging (Maceroni et al. 1994). Another observable for the mass transfer may be how the polarization feature changes with phase. Oshchepkov (1973) acquired polarimetric observations of YY Eri, where a polarization maximum just appears at phase 0.25. This provides good evidence for the mass transfer.

Usually, the cyclic period change may be caused by three distinct mechanisms: (1) the apsidal motion, (2) the light-time effect of a third body, (3) the magnetic activity cycle in the components. Firstly, the apsidal

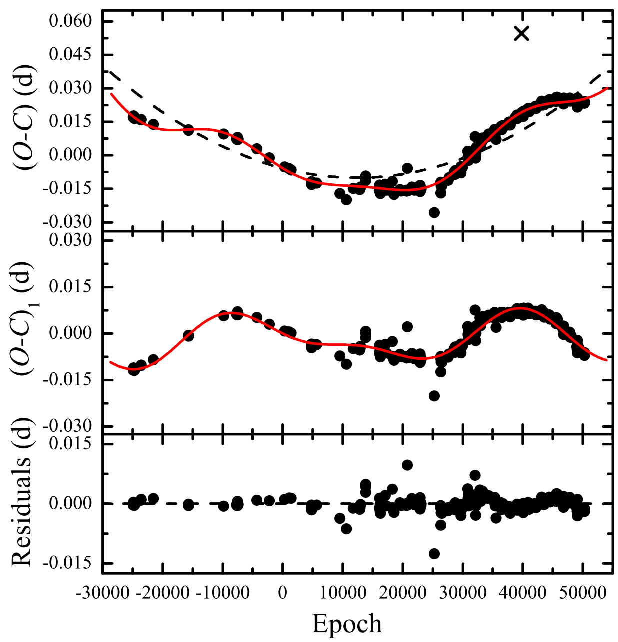

Fig. 1 *Top*: $(O-C)$ diagram of YY Eri based on Eq. (1) and the fitting curves. The *dashed* and *solid lines* represent the parabolic fit and the full contribution of Eqs. (2) and (3) respectively. *Middle*: the residuals $(O-C)_1$ and the double-sine fitting curve of Eq. (3). *Bottom*: the final residuals.

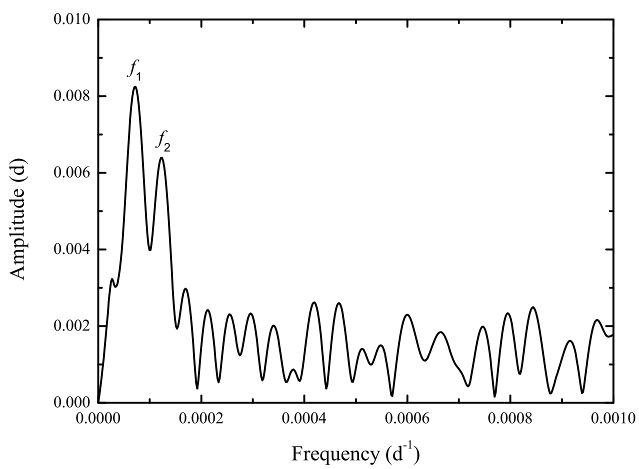

Fig. 2 Fourier power spectrum of $(O-C)_1$ residuals.

motion is not sufficient to explain the periodic changes of light-minimum times of YY Eri, since both the primary and secondary times of light minimum follow the same general trend of the $O-C$ variation. Secondly, if we assume that the modulation period of $38.6192\,\mathrm{yr}$ is caused by the light-time effect of a third body, the mass function for the third body can be calculated to be $f(m) = 0.0010(\pm 0.0002)\,M_\odot$ by using the well-known formula

$$\begin{aligned} f(m) &= \frac{M_3^3 \sin^3 i'}{(M_1+M_2+M_3)^2} \\ &= \frac{4\pi^2}{GP_{\mathrm{mod}}^2} \times (a_{12}\sin i')^3, \end{aligned} \tag{5}$$

where $a_{12}\sin i' = A\times c$ (A is the semi-amplitude and c is the speed of light). In Equation (5), M_3, i', P_{mod} and a_{12}

Table 2 Photoelectric and CCD Times of Light Minima of YY Eri Collected from the Literature

HJD2400000+	Type	Error	Method	Ref.	HJD2400000+	Type	Error	Method	Ref.
33989.1691	I	-	pe	[1]	46026.2641	I	0.0003	pe	[7]
34004.1188	II	-	pe	[2]	46027.2304	I	0.0003	pe	[7]
36541.6889	II	-	pe	[2]	46028.1945	I	0.0003	pe	[7]
39120.2503	I	-	pe	[3]	46028.3558	II	0.0007	pe	[7]
39124.1085	I	-	pe	[3]	47080.1707	I	0.0005	pe	[5]
39162.2058	II	-	pe	[3]	47128.3933	I	0.0003	ccd	[6]
39165.0999	II	-	pe	[3]	47530.4227	II	0.0007	ccd	[6]
39165.2596	I	-	pe	[3]	47537.3346	I	0.0004	ccd	[6]
39166.2241	I	-	pe	[3]	47862.3702	I	0.0004	ccd	[6]
39167.1886	I	-	pe	[3]	47918.3099	II	0.0004	ccd	[6]
39181.1742	II	-	pe	[3]	48262.3127	I	0.0008	ccd	[6]
39187.1216	I	-	pe	[3]	48268.2594	II	0.0004	ccd	[6]
41928.5121	I	-	pe	[4]	48277.2616	II	0.0002	ccd	[6]
43118.8477	II	-	pe	[4]	48646.3410	II	0.0004	ccd	[6]
43119.8128	II	-	pe	[4]	48654.2169	I	0.0004	ccd	[6]
43123.8303	I	-	pe	[4]	48935.5275	I	0.0004	ccd	[6]
43124.7948	I	-	pe	[5]	48952.4061	II	0.0007	ccd	[6]
45709.9487	I	0.0003	ccd	[6]	48978.2861	I	0.0003	ccd	[6]
45710.1101	II	0.0002	ccd	[6]	48980.3760	II	0.0003	ccd	[6]
45726.0239	I	0.0006	ccd	[6]	48987.4488	II	-	pe	[6]
45740.0097	II	0.0002	ccd	[6]	48993.3960	I	-	pe	[6]
45757.8529	I	-	pe	[5]	57431.6025	II	0.0001	ccd	[8]
46026.1049	II	0.0004	pe	[7]	-	-	-	-	-

Note: "pe" refers to photoelectric data. References: [1] Huruhata et al. 1953; [2] Purgathofer & Purgathofer (1960); [3] Bhattacharyya (1967); [4] Eaton (1986); [5] Budding et al. (1996); [6] Kim et al. (1997); [7] Yang & Liu (1999); [8] Samolyk (2016).

Table 3 Orbital Parameters of the Third Body in YY Eri

Parameter	Value	Unit
A	$0.0065(\pm 0.0003)$	d
P_3	$38.6192(\pm 0.7379)$	yr
$f(M)$	$0.0010(\pm 0.0002)$	$M_\odot$
$M_3(i' = 90°)$	$0.1741(\pm 0.0123)$	$M_\odot$
$M_3(i' = 70°)$	$0.1859(\pm 0.0132)$	$M_\odot$
$M_3(i' = 50°)$	$0.2310(\pm 0.0166)$	$M_\odot$
$M_3(i' = 30°)$	$0.3672(\pm 0.0273)$	$M_\odot$
$a_3(i' = 90°)$	$13.9857(\pm 0.3252)$	AU
$a_3(i' = 70°)$	$13.9387(\pm 0.3268)$	AU
$a_3(i' = 50°)$	$13.7631(\pm 0.3329)$	AU
$a_3(i' = 30°)$	$13.2639(\pm 0.3498)$	AU

are the mass of the third body, the inclination of the triple system, the modulation period and the semimajor axis of the eclipsing binary, respectively. The masses and orbital radii of the third body for several different inclinations are listed in Table 3. In this calculation, a total mass of 2.16 $M_\odot$ is adopted for the eclipsing binary (Nesci et al. 1986). From Table 3, we find that the mass of the third body is relatively small, thus it will be difficult to detect the spectrum of a tertiary star. The relation between mass M_3 and orbital inclination i' is plotted in Figure 3. If the

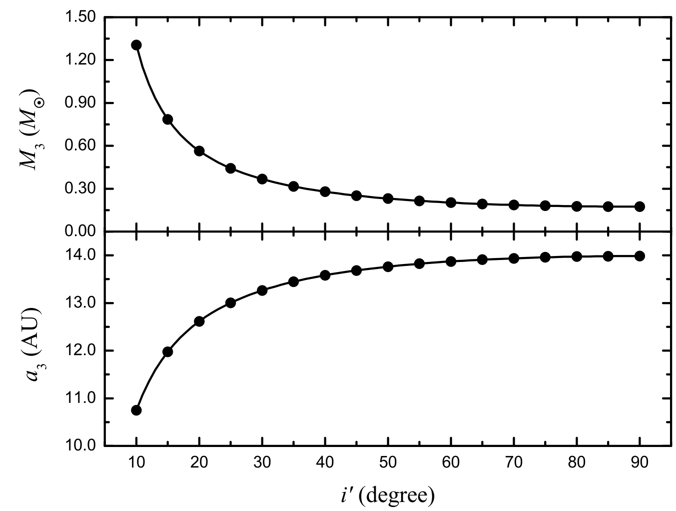

Fig. 3 *Upper panel*: correlation between the third-body mass M_3 and the orbital inclination i'. *Lower panel*: correlation between the orbital radius of the third body a_3 and the orbital inclination i'.

third body is in a coplanar orbit with the system YY Eri (i.e., $i' = 80.8°$), its mass can be estimated as $M_3 = 0.1764(\pm 0.0125)\,M_\odot$. In this case, the third body should be a cool stellar object.

With the assumption of a third body, the semi-amplitude of the radial velocity for the mass center of the binary system, relative to the mass center of the triple system, may be estimated to be $V_c = 0.8686\,\mathrm{km\,s^{-1}}$. Theoretically, the radial velocity with respect to the mass center of the triple system could influence observations of the traditional heliocentric radial velocity of the barycenter and generate different observed values at different times. By retrospecting previous spectral observations, we found the radial velocity $V_0 = -20\,\mathrm{km\,s^{-1}}$ obtained by Struve (1947) and another value $V_0 = -15\,\mathrm{km\,s^{-1}}$ derived by Nesci et al. (1986). A remarkable difference could be found. However, it is not certain whether this difference is caused by perturbations from a third star or by observational uncertainties, because the calculated V_c is much smaller than the observed V_0, and even smaller than the error of about 10% on the velocity amplitudes estimated by Nesci et al. (1986).

Finally, the periodic variation of $22.3573\,\mathrm{yr}$ may be caused by cyclic magnetic activity of the primary component since photometric solutions provided by both Maceroni et al. (1994) and Vilhu & Maceroni (2007) suggested that active spots appear on the primary star of YY Eri, and explicitly determined the primary component to be a magnetically active star. A theoretical model of this mechanism has been proposed by Applegate (1992) and developed by Lanza et al. (1998) and Lanza & Rodonò (2002). During its magnetic activity cycle, the changes of angular momentum due to a varying magnetic field distribution result in changes to the gravitational quadrupole moment, modulating the orbital period. In the case of conservative angular momentum, when the gravitational quadrupole moment increases, the component moves closer to its orbit and its velocity will become faster under a stronger gravitational force, thus the orbital period decreases. Otherwise, the orbital period increases. Using the formula

$$\Delta P = 2\pi A \frac{P}{P_{\mathrm{mod}}}, \tag{6}$$

the orbital period modulation can be calculated to be $\Delta P = 0.8707 \times 10^{-6}\,\mathrm{d}$ and the rate of period change $\Delta P/P = 2.7084 \times 10^{-6}$ can be obtained with $P_{\mathrm{mod}} = 22.3573\,\mathrm{yr}$ and $A = 0.0035\,\mathrm{d}$ as derived from Equation (3). By inserting the absolute elements: $M_1 = 1.54\,M_\odot$, $M_2 = 0.62\,M_\odot$, $R_1 = 1.20\,R_\odot$ and $R_2 = 0.77\,R_\odot$ (Nesci et al. 1986), and the separation between the two components $a = 2.5508\,R_\odot$, derived from Kepler's third law, inserted into the following formula (Lanza et al. 1998)

$$\frac{\Delta P}{P} = -9\left(\frac{R}{a}\right)^2 \frac{\Delta Q}{MR^2}, \tag{7}$$

the variation of quadrupole moment $\Delta Q_1 = 2.9078 \times 10^{49}\,\mathrm{g\,cm^2}$ and $\Delta Q_2 = 1.1707 \times 10^{49}\,\mathrm{g\,cm^2}$ can be estimated for the primary star and the secondary star, respectively. These variations in quadrupole moment are at the required order of $\Delta Q \sim 10^{49}\,\mathrm{g\,cm}^2$ (Lanza et al. 1998).

The mechanism provided by Applegate (1992) typically requires luminosity variability $\Delta L/L < 0.1$, which can be calculated by using the following equation deduced by Yu et al. (2015)

$$\frac{\Delta L}{L} = \frac{5G^2}{24\pi^2\sigma}\frac{M^3}{R^6}\Big(\frac{a}{RT}\Big)^4\frac{(\Delta P)^2}{P_{\rm mod}}. \quad (8)$$

In this equation, G, σ and T represent the gravitational constant, the Stefan-Boltzmann constant and the surface temperature of the active star, respectively. All these physical elements are in the International System of Units. With Equation (8), we have calculated $\Delta L_1/L_1 = 0.0277$ for the primary and $\Delta L_2/L_2 = 0.1285$ for the secondary. This implies that cyclic changes in the orbital period of YY Eri may be caused by cyclic magnetic activity of its primary star.

Two observed periodic changes in the orbital period of YY Eri have been plausibly interpreted by the light-time effect due to an unseen third star and the cyclic magnetic activity modulation, respectively. However, for interpreting the third body, it is not certain whether the difference in radial velocities obtained by Struve (1947) and Nesci et al. (1986) is rooted in perturbations from a third star, or observational uncertainties. For the periodic variation of $22.3573\,$yr, the evidence of long-term luminosity variations provided by Kim et al. (1997) may support the magnetodynamic explanation. Moreover, it is the primary's magnetic activity cycle that causes the cyclic period variation, which is in concordance with the photometric results (i.e., the active spots appear on the primary star of YY Eri). However, the present magnetic activity cycle from both the $(O-C)$ diagram and spectral analysis deviates from the period revealed by Kim et al. (1997). We should further explore additional evidence of magnetic activity (e.g., maculation effects in the photometry or cyclic effects in emission lines) in the future to resolve this issue firmly.

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