

## YY GEMINORUM: A VERY LATE TYPE CLOSE BINARY WITH POSSIBLE MAGNETIC STELLAR WIND

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### ABSTRACT

The  $O-C$  curve of the very late type close binary (dM1e + dM1e) YY Geminorum is formed and analyzed based on all available times of minimum light. It is found that the orbital period shows a secular decrease with rate  $dP/dt = -1.08 \times 10^{-8}$  days  $\text{yr}^{-1}$ . There is weak evidence indicating that a small-amplitude period oscillation is superposed on the period decrease. YY Gem is a well-detached eclipsing binary containing two very active components. The secular period decrease may suggest that the system is undergoing secular mass and angular momentum loss via a magnetic stellar wind. If the small-amplitude oscillation is real, it can be explained either by magnetic activity cycles or by the presence of a giant planet or brown dwarf.

*Key words:* binaries: close — stars: individual (YY Geminorum) — stars: mass loss

### 1. INTRODUCTION

YY Geminorum is a short-period ( $P = 0.81428254$  days) eclipsing binary whose components belong to the sextuple system Castor (Castor C). Since it has many interesting and challenging characteristics, YY Gem has been extensively investigated, and several hundred papers have been published on it since its discovery. It is a double-lined spectroscopic binary system consisting of two M-type dwarfs (dM1e + dM1e) that are detached from the critical Roche lobe (Joy & Sanford 1926; Leung & Schneider 1978). Flare activity on this binary star was first reported by Moffett & Bopp (1971), and it is one of the most active flare stars (Moffett 1974; Doyle & Butler 1985; Doyle & Mathioudakis 1990). Early photometric studies were summarized by Kron (1952), who observed a second order of light variations superposed on the first-order eclipse-related light changes, a finding later confirmed by Leung & Schneider (1978) and by Mallama (1980). By combining Bopp's (1974) spectroscopic solution with their photometric parameters, Leung & Schneider determined the absolute dimensions of both components.

YY Gem exhibits many of the phenomena common to the RS Canum Venaticorum stars, such as starspots and flare activity (Kron 1952; Moffett & Bopp 1971), strong emission cores in the H and K lines of Ca II, and X-ray, extreme-UV, and radio emission. Therefore it was listed as a sample star in the second edition of Strassmeier et al.'s (1993) catalog of chromospherically active binary stars. However, the active components of the RS CVn stars are usually a G- or K-type subgiant and a slightly early star on or near the main sequence, whereas YY Gem consists of two dM1 stars that are either on the late pre-main-sequence contraction phase or a zero-age main sequence (Chabrier &

Baraffe 1995; Leung & Schneider 1978). Orbital period change is a common property of the RS CVn stars; does the orbital period of YY Gem change as in the RS CVn stars? In the present paper, all available times of minimum light for this binary are collected, and the changes in the period are analyzed. Then the mechanisms that might cause the period changes are discussed.

### 2. ORBITAL PERIOD VARIATIONS FOR YY GEMINORUM

Epochs and orbital periods of YY Gem have been given by several authors (e.g., Mallama 1980; Zsoldos 1986). Leung & Schneider (1978) proposed that the orbital period of YY Gem is increasing rapidly. However, the study by Mallama (1980) showed that the apparently rapid increase was caused by Leung & Schneider's erroneous measurement of the period for YY Gem. In order to check whether the period is variable and to understand the properties of the period change, all available times of minimum light of the binary star have been collected. These timings are listed in the first column of Table 1; in the second column are shown the observation methods, where "pg" refers to photographic, "vis" to visual, and "pe" to photoelectric observations. The  $O-C$  values of those times of minimum light were computed with the following ephemeris:

$$\text{Min. I} = \text{HJD } 2,424,595.8172 + 0.81428254E, \quad (1)$$

where HJD 2,424,595.8172 is the time of conjunction, 0.81428254 days is the constant ephemeris period  $P_e$ , and  $E$  is the cycle. Since the  $O-C$  values for the visual and the photographic data show large scatter, in the present study we calculate and use only the  $O-C$  values for the photoelectric data, starting with the first photoelectric timing. The  $O-C$  values are listed in the fifth column of Table 1 and are represented graphically against  $E$  in Figure 1, where open circles refer to visual or photographic data and filled circles refer to photoelectric observations.

As shown in Figure 1, the orbital period of YY Gem is variable, and the general trend of the  $O-C$  curve is toward a downward parabolic variation, indicating a secular period decrease. With a weight of 1 assigned to the visual and photographic observations and 8 to the photoelectric data, a weighted least-squares solution yields the following qua-

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TABLE 1  
TIMES OF MINIMUM LIGHT FOR YY GEMINORUM

HJD (2,400,000+)	Meth.	Min.	$E$	$O-C$	$(O-C)'$	Ref.
24,500.55.....	pg	I	-117	+0.0039	+0.0033	1
24,573.42.....	pg	II	-27.5	-0.0044	-0.0050	1
24,584.41.....	pg	I	-14	-0.0072	-0.0078	1
24,591.34.....	pg	II	-5.5	+0.0014	+0.0008	1
24,595.41.....	pg	II	-0.5	-0.0001	-0.0007	1
24,619.43.....	pg	I	29	-0.0014	-0.0020	1
24,639.39.....	pg	II	53.5	+0.0087	+0.0081	1
24,791.65.....	pg	II	240.5	-0.0022	-0.0029	2
24,848.65.....	pg	II	310.5	-0.0019	-0.0026	2
24,875.53.....	pg	II	343.5	+0.0067	+0.0060	2
24,916.65.....	pg	I	394	+0.0055	+0.0048	2
24,920.31.....	pg	II	398.5	+0.0012	+0.0005	2
24,921.53.....	pg	I	400	-0.0002	-0.0009	2
24,922.34.....	pg	I	401	-0.0045	-0.0052	2
24,961.43.....	pg	I	449	-0.0001	-0.0008	2
25,230.55.....	pg	II	779.5	-0.0004	-0.0011	2
25,234.62.....	pg	II	785.5	-0.0019	-0.0026	2
25,242.36.....	pg	I	794	+0.0025	+0.0018	2
25,687.37.....	pg	II	1340.5	+0.0071	+0.0064	2
25,698.36.....	pg	I	1354	+0.0042	+0.0035	2
27,158.36.....	vis	I	3147	-0.0044	-0.0051	3
27,160.40.....	vis	II	3149.5	-0.0001	-0.0008	3
28,545.49.....	vis	II	4850.5	-0.0047	-0.0053	3
28,571.52.....	vis	II	4882.5	-0.0017	-0.0023	3
28,596.39.....	vis	I	4913	+0.0027	+0.0021	3
29,639.48.....	vis	I	6194	-0.0033	-0.0037	3
30,466.39.....	vis	II	7209.5	+0.0028	+0.0025	3
32,605.9146....	pe	I	9837	+0.0001	+0.0002	4
32,965.8275....	pe	I	10279	+0.0001	+0.0003	4
40,968.99710...	pe	II	20107.5	-0.0063	-0.0029	5
40,969.81559...	pe	II	20108.5	-0.0021	+0.0013	5
40,970.63280...	pe	II	20109.5	-0.0008	+0.0026	5
40,971.85624...	pe	I	20111	+0.0029	+0.0063	5
42,829.634.....	pe	II	22392.5	-0.0050	-0.0006	6
43,949.679.....	pe	I	23768	-0.0060	-0.0009	7
43,960.6731....	pe	II	23781.5	-0.0044	+0.0007	7
43,969.6277....	pe	II	23792.5	-0.0068	-0.0017	7
46,017.55.....	pe	II	26307.5	-0.0051	+0.0014	8
46,019.58.....	pe	I	26310	-0.0108	-0.0043	9
47,208.4305....	pe	I	27770	-0.0133	-0.0059	10
50,896.3199....	pe	I	32299	-0.0091	+0.0014	11
51,163.4047....	pe	I	32627	-0.0089	+0.0018	11
51,165.4400....	pe	II	32629.5	-0.0093	+0.0014	11

REFERENCES.—(1) Van Gent 1926; (2) van Gent 1931; (3) Binnendijk 1950; (4) Kron 1952; (5) Leung & Schneider 1978; (6) Mallama et al. 1977; (7) Mallama 1980; (8) Geyer & Kämper 1985; (9) Zsoldos 1986; (10) Diethelm 1988 (11) Agerer & Hübscher 1999.

dratic ephemeris:

$$\text{Min. I} = \text{HJD } 2,424,595.8178(1) + 0.81428258(1)E - 1.20(2) \times 10^{-11} E^2. \quad (2)$$

With this ephemeris, a continuous period-decrease rate  $dP/dt = -1.08 \times 10^{-8}$  days  $\text{yr}^{-1}$  is obtained, which is equivalent to a loss of 0.09 s per century. This decrease rate is rather small when compared with the values for other close binaries.

It can be seen in Figure 1 that the quadratic ephemeris (eq. [2]) represents only a mean trend (*solid line*) without describing any particular characteristics, and upon which

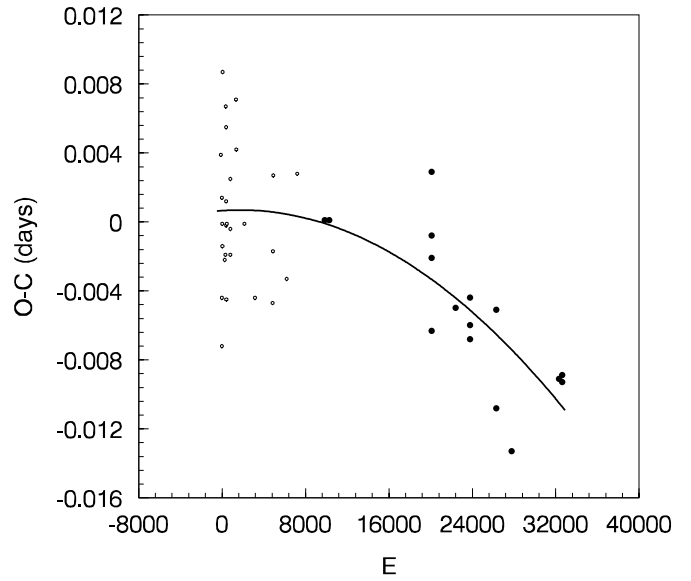


FIG. 1.—The  $O-C$  curve of the short-period close binary YY Gem. The solid line indicates the general trend.

may be superposed an oscillatory component. The  $(O-C)'$  residuals from this quadratic ephemeris are listed in Table 1, and those  $(O-C)'$  values for all the photoelectric data are displayed separately in Figure 2. As one can see, the  $(O-C)'$  residuals for the photoelectric data may show an alternating deviation, indicating that there may be a periodic variation in the change of the orbital period. A least-squares solution leads to

$$(O-C)' = -0.0007 + 0.0024 \sin(0^{\circ}0270E + 259^{\circ}8) \text{ days}. \quad (3)$$

This formula suggests an oscillation with a period of about  $T = 29.7$  yr and an amplitude of about  $A = 0.0024$  days. Using the equation

$$\Delta P = \sqrt{2[1 - \cos(2\pi P_e/T)]} A, \quad (4)$$

the amplitude of the orbital period change can be calculated to be  $\Delta P = 1.5 \times 10^{-6}$  days. However, since our inference of the oscillation is based on the  $(O-C)'$  residuals of only 16 photoelectric data points, we do not know whether the var-

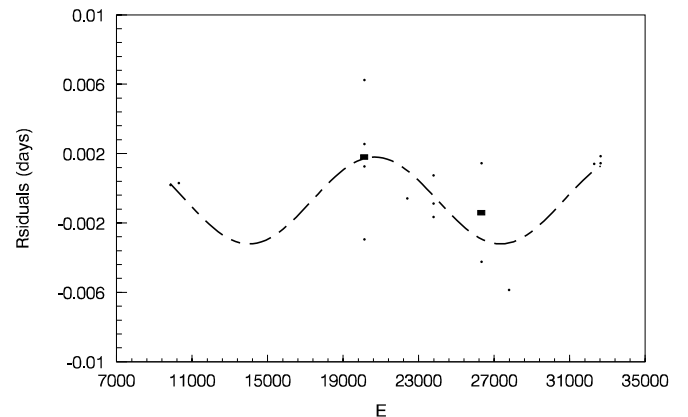


FIG. 2.—Residuals of YY Gem based on the quadratic ephemeris, and their description by a possible periodic ephemeris.

iation is continuous or not. Moreover, the amplitude of the oscillation is rather small; in order to verify it, more high-precision times of minimum light are required.

### 3. MECHANISMS FOR ORBITAL PERIOD VARIATION

#### 3.1. Nonperiodic Mechanisms

The photometric study by Leung & Schneider (1978) showed that YY Gem is a well-detached close binary in which neither component is filling the critical Roche lobe. The secular period decrease cannot be plausibly explained by mass transfer between the components. YY Gem is one of the most active flare stars (Moffett 1974; Doyle & Butler 1985; Doyle & Mathioudakis 1990). Flare activity is probably directly responsible for mass ejection, and magnetic coupling between the magnetic field and ejected particles may cause a great deal of angular momentum loss (AML). Therefore, the period decrease can be interpreted as AML via a magnetic stellar wind.

If the period change of YY Gem is caused by AML, then we can calculate the rate of angular momentum loss with a rather general equation (as described in detail by Vilhu 1992):

$$dJ/dt = -1.0 \times 10^{42} K^2 f^{-2} M R^\gamma (P/3)^{-\alpha}, \quad (5)$$

where  $M$  and  $R$  are the mass and the radius of the component,  $P$  is the orbital period, and  $K^2$  is the gyration constant. Taking for these parameters  $K^2 = 0.1$  (for main-sequence stars),  $\gamma = 2$ ,  $\alpha = 1.5$ , and the values of  $f$  calculated from  $f = (3.3 - 2.3m)^{-1}$  with  $m$  the mass in solar units, the AML rates are determined to be  $-6.8 \times 10^{41}$  and  $-5.4 \times 10^{41}$  g cm<sup>2</sup> s<sup>-1</sup> yr<sup>-1</sup>, which correspond to orbital period decrease rates of  $-2.72 \times 10^{-10}$  and  $-2.17 \times 10^{-10}$  days yr<sup>-1</sup> for the two components. The computed period-decrease rates are 2 orders of magnitude smaller than the observed value. With Guinan & Bradstreet's (1988) equation

$$dP/dt = -1.1 \times 10^{-8} q^{-1} (1+q)^2 (M_1 + M_2)^{-5/3} K^2 \times (M_1 R_1^4 + M_2 R_2^4) P^{-7/3}, \quad (6)$$

and again taking the value  $K^2 = 0.1$ , a period-decrease rate  $dP/dt = -1.01 \times 10^{-9}$  days yr<sup>-1</sup> is obtained, which is also smaller than the observed rate.

#### 3.2. Periodic Mechanisms

In this subsection, we assume that the period oscillation proposed in § 2 is real and investigate possible physical

mechanisms. The periodic mechanisms are the light-time effect due to the existence of a third body and magnetic activity cycles.

With the semi-amplitude of  $O-C$  oscillation, the dimension of the eclipsing pair moving around the center of mass of the assumed triple system is determined to be  $a'_{12} \sin i = 0.42$  AU. Then, using the equation

$$f(m) = \frac{(M_3 \sin i')^3}{(M_1 + M_2 + M_3)^2} = \frac{4\pi^2}{GT^2} (a'_{12} \sin i')^3, \quad (7)$$

we obtain a very small mass function,  $f(m) = 8.2 \times 10^{-5} M_\odot$ , for the additional body. In this formula  $M_1$ ,  $M_2$ , and  $M_3$  are the masses of the eclipsing pair and the third body, respectively,  $G$  is the gravitational constant,  $T$  is the period of the  $O-C$  oscillation, and  $i'$  is the orbital inclination of the third body. Taking the absolute parameters published by Leung & Schneider (1978),  $M_1 = 0.62 M_\odot$  and  $M_2 = 0.57 M_\odot$ , the values of the masses and the orbital radii of the third body for several different values of  $i'$  were computed and are shown in Table 2. As listed in the table, for a somewhat large orbital inclination (i.e.,  $i' > 30^\circ$ ), the third companion should be a giant planet or a brown dwarf. In these cases, the supposed third body is very difficult to detect because its luminosity is extremely low.

YY Gem contains two very active flare stars (dM1e + dM1e). A study by Chabrier & Baraffe (1995) has shown that YY Gem develops a radiative core over  $\sim 70\%$  of the radius and possesses a thick convective envelope (cover  $\sim 30\%$  in radius). The oscillation in the orbital period of YY Gem may be a consequence of possible magnetic cycles in the components. Applegate (1992) proposed that a quasi-periodic exchange of angular momentum between the inner and the outer parts in the convection zone may induce a modulation of its quadrupole moment and, therefore, change the orbital period. Recently, Lanza, Rodonò, & Rosner (1998) pointed out that apart from the redistribution of the internal angular velocity, the change in the azimuthal field intensity can likewise produce a change in the oblateness of the active component, and the stability of the azimuthal magnitude field has been discussed with consideration of a more general magnetic field geometry (Lanza & Rodonò 1999). The physical parameters given by Leung & Schneider (1978) are  $M_1 = 0.62 M_\odot$ ,  $R_1 = 0.66 R_\odot$ ,  $M_2 = 0.57 M_\odot$ ,  $R_2 = 0.58 R_\odot$ , and  $P = 0.82$  days. Using Kepler's third law,  $(M_1 + M_2) = 0.0134a^3/P^2$ , the separation between the components is determined to be  $a = 3.9 R_\odot$ . If the period oscillation of the binary star is caused by magnetic activity cycles in the components, then, inserting

TABLE 2  
MASS AND ORBIT RADIUS FOR THE ASSUMED THIRD BODY  
IN YY GEMINORUM

Parameter	Value	Parameter	Value
$A$ (days) .....	0.0024	$a'_{12} \sin i'$ (AU)	0.42
$T$ (yr).....	29.7	$f(m) (M_\odot)$ .....	$8.2 \times 10^{-5}$
$m_3 (M_\odot)$ :		$a_3$ (AU):	
$i' = 90^\circ$ .....	0.050	$i' = 90^\circ$ .....	10.0
$i' = 70^\circ$ .....	0.053	$i' = 70^\circ$ .....	10.0
$i' = 50^\circ$ .....	0.066	$i' = 50^\circ$ .....	9.89
$i' = 30^\circ$ .....	0.103	$i' = 30^\circ$ .....	9.70
$i' = 10^\circ$ .....	0.330	$i' = 10^\circ$ .....	8.72

those parameters into the equation

$$\frac{\Delta P}{P} = -9 \left( \frac{R}{a} \right)^2 \frac{\Delta Q}{MR^2}, \quad (8)$$

the required changes in the quadrupole moment necessary to reproduce an orbital period change  $\Delta P = 1.5 \times 10^{-6}$  days are calculated to be  $\Delta Q = 1.85 \times 10^{49}$  and  $\Delta Q = 1.70 \times 10^{49}$  g cm<sup>2</sup>, respectively, for each component.

#### 4. DISCUSSION AND CONCLUSIONS

The analysis of the  $O-C$  curve of YY Geminorum has shown that the orbital period of the system is decreasing. Weak evidence indicates that a small-amplitude oscillation is superposed on the secular period decrease. The two eclipsing minima in the light curve of YY Gem are very sharp and deep (up to 0.7 mag in  $V$ ; Leung & Schneider 1978; Mallama 1980), and times of minimum light can be determined to high precision. Therefore, the period changes of YY Gem may be reliable. The present study has shown that YY Gem does share the RS CVn tendency for period changes, but with a small amplitude of period change both in secular change and in cyclic oscillation.

For magnetic braking to work, we need to know that the system is in synchronized rotation. A good example of synchronized rotation is our Moon in the Earth-Moon system. With the parameters given by Leung & Schneider (1978), the tidal force on the components of YY Gem is calculated to be  $F = 6.3 \times 10^{17} F_{EM}$ , where  $F_{EM}$  is the tidal force between Earth and the Moon. This result suggests that  $F$  is much larger than  $F_{EM}$ , and thus we can conclude that YY Gem is in synchronized rotation. Although the secular decrease can be plausibly explained by AML via a magnetic stellar wind, the calculated period decrease rate is much smaller than the observed value. This may suggest that those formulae cannot be used for M-type dwarfs. On the other hand, the secular decrease may be part of a long-periodic change. However, this will require more times of minimum light to ascertain in the future.

Apart from the main decrease in the orbital period, the  $(O-C)$  curve indicates that there seems to exist a very small amplitude oscillation in the orbital period, which can be explained either by magnetic activity cycles or by the pres-

ence of a giant planet or a brown dwarf. However, as displayed in Figure 2, although the  $(O-C)$  curve can be described by a periodic ephemeris, the time interval between the observations is very large, and the oscillation is only based on 16 photoelectric data points. Moreover, the amplitude of this oscillation is very small at  $A = 0.0024$  days, which is comparable to the precision of the photoelectric data. In order to verify the prediction of a change in the orbital period, more high-precision photoelectric and CCD timings are needed.

YY Gem shares all the properties of the short-period ( $P < 1$  day) RS CVn stars (e.g., ER Vul, UV Psc, BH Vir, XY UMa, CG Cyg, and SV Cam). They contain two main-sequence dwarfs that are detached from the critical Roche lobe. The oscillation in the orbital period is typical for this kind of RS CVn star. Other examples are the 30 yr cycle in ER Vul (G0 V + G5 V,  $P = 0.69809409$  days; Qian, Liu, & Yang 1998), the 61 yr cycle in UV Psc (G2 V + K0 V,  $P = 0.8610482$  days; Qian, Liu, & Yang 1999), the 9.1 yr cycle for BH Vir (G0 V + G2 V,  $P = 0.81687161$  days; Qian, Liu, & Tan 2000), the 30.5 yr cycle in XY UMa (G3 V + K4-K5 V,  $P = 0.478994587$  days; Chochol et al. 1998), the 50 yr cycle in CG Cyg (G9.5 V + K3 V,  $P = 0.63114100$  days; Hall 1991), and the 73 yr cycle in SV Cam (G5 V + G3 V,  $P = 0.59306995$  days; Hall & Kreiner 1980). These period oscillations are more plausibly explained by magnetic activity cycles of the active components. The very small amplitude of the period oscillation in YY Gem may result from the very late types of the two components (dM1e + dM1e). The mean densities of the two active stars of YY Gem are much higher than those of other short-period RS CVn stars. During the magnetic cycle, the structure change in YY Gem may be harder than those of the others and result in a smaller variation of the quadrupole moment  $\Delta Q$ , thus causing the smaller amplitude period oscillation.

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