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A PERIOD INVESTIGATION OF THE SX PHOENICIS STAR DY PEGASI

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ABSTRACT

We measure two new times of light maximum of the SX Phoenicis star DY Pegasi in 2008 December and collect 410 pe/CCD times of light maximum that had been published. These data could be modeled with a nonlinear fit including a continuously decreasing period change ($dP/dt = -9.04 \times 10^{-12}$ days day^{-1}) and a periodic change with a period of 42.2 yr. If this periodic change is caused by the light traveling time effect of an orbital motion of DY Pegasi in a binary system, the deduced mass of the companion could be 0.028 $M_\odot$ and it is probably a brown dwarf.

Key words: stars: individual (DY Pegasi) – stars: variables: delta Scuti – techniques: photometric

Online-only material: machine-readable and VO tables

1. INTRODUCTION

DY Pegasi ($\alpha_{2000} = 23^{h}08^{m}51\overset{s}{.}2$, $\delta_{2000} = +17°12'56''$, $V = 10.26$, $\Delta V = 0.54$, Sp: A3-F1) is one of the 13 known field SX Phoenicis stars (Rodríguez & Breger 2001). SX Phoenicis stars are the δ Scuti stars of Population II and old disk population. Most of them display visual high amplitudes larger than 0.3 minutes with short periods $\lesssim$0.08 days. The period changes predicted by evolution models for the pulsating stars in the lower instability strip are generally positive (Rodríguez et al. 1995). Nevertheless, the decreasing periods that are not in agreement with these predictions are observed in some SX Phoenicis stars (e.g., CY Aqr; Fu & Sterken 2003). Breger & Pamyatnykh (1998) also pointed out that some of these types of stars are characterized by a sudden jump on the order of $\Delta P/P \sim 10^{-6}$. But recently, some authors have found that their period changes can be better described by a secular increase/decrease of the period, in addition to an orbital motion in a binary (CY Aqr, Fu & Sterken 2003; BL Cam, Fauvaud et al. 2006; KZ Hya, Fu et al. 2008).

DY Pegasi was reported as a variable star by Morgenroth (1934) and the light curves were first determined by Soloviev (1938, 1940). Kozar (1980) and Garrido & Rodríguez (1996) presented some evidence for secondary periodicity. The period changes of DY Pegasi were calculated by a number of authors, and different values were obtained (see Table 3 in Hintz et al. 2004). After removing the contribution from the long-term period change, the cyclic variations in the residuals were observed (Hintz et al. 2004; Derekas et al. 2009). The latest detailed work was provided by Fu et al. (2009), who modeled the times of light maximum with a fit concerning a continuously increasing period change combined with the light traveling time effect of an orbital motion, but the value of the orbital period obtained by them was larger than the span of the data.

In order to investigate the period change of DY Pegasi, we collected all the pe/CCD times of light maximum that had been published and analyzed the $O - C$ diagram with a nonlinear fit. This paper reports observations and analysis of pulsations in Sections 2 and 3. Sections 4 and 5 present the discussions and conclusions, respectively.

2. OBSERVATIONS

Observations of DY Pegasi were carried out on 2008 December 12 and 17, using the 80 cm telescope and 50 cm telescope at Xinglong observation station of the National Astronomical Observatories of the Chinese Academy of Sciences (NAOC). The telescopes were equipped with the PI VA1300B cameras which had 1340×1300 square pixels. Exposure times ranged from 10 to 20 s depending on the diameter of the telescopes and nightly seeing. All observations were reduced using standard IRAF procedures. GSC01712−00984 ($\alpha_{2000} = 23^{h}09^{m}05^{s}$, $\delta_{2000} = +17°08'21''$, 9.91V, HD 218587) was selected as a comparison star and the check star was GSC01712−01246 ($\alpha_{2000} = 23^{h}08^{m}41^{s}$, $\delta_{2000} = +17°08'15''$, 11.1V). Based on the new observations, two new times of light maximum were determined by fitting a third-degree polynomial on each observed peak (see Table 1).

3. ANALYSIS OF THE $O - C$ DIAGRAM

The $O - C$ analyses of DY Pegasi have been done by many authors and a great deal of times of light maximum have been observed visually since it was reported as a variable star. Grigorevski & Mandel (1960) gave hundreds of times of light maximum, most of which were obtained by visual observations and photographic observations. The recent collecting work was done by Fu et al. (2009) who gave 398 times of light maximum in total. Based on their work, we collected 410 pe/CCD times of light maximum (Table 1) for our $O - C$ analysis. Forty-one times of light maximum given by Peña & Peniche (1986) and Klingenberg et al. (2006) were not listed, because most of the data were dispersed. Some data with unusually large error were not used in the analysis.

It is supposed that the variation in the $O - C$ diagram is caused by the linear change of the pulsation period of the star and by a light traveling time effect of the star orbiting in a binary system of an elliptical orbit (Paparó et al. 1988):

$$C = C_A + C_B, \tag{1}$$

$$C_A = (T_0 + \delta T_0) + (P_0 + \delta P_0)E + \frac{\beta}{2}E^2, \tag{2}$$

$$\begin{aligned} C_B &= A\left[(1 - e^2)\frac{\sin(\nu + \omega)}{1 + e\cos\nu} + e\sin\omega\right] \\ &= A\left[\sqrt{1 - e^2}\sin E^*\cos\omega + \cos E^*\sin\omega\right], \end{aligned} \tag{3}$$

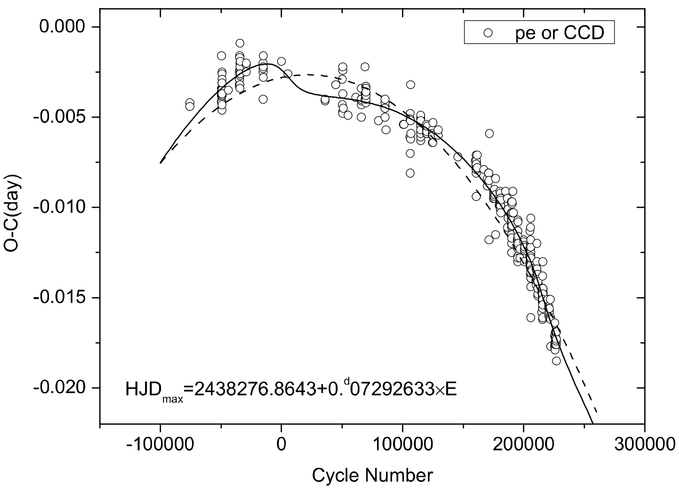

Figure 1. $O - C$ diagram for DY Pegasi. The ephemeris 2438276.8643 days + $0.07292633E$ days is obtained from the period correction of Equation (4) in Hintz et al. (2004). The solid line shows the fit containing a decreasing period change and the light traveling time effect component.

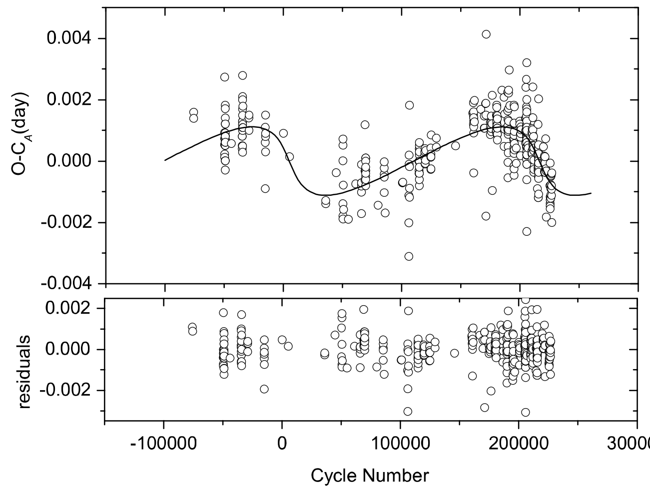

Figure 2. $O - C$ diagram for DY Pegasi. The component of the decreasing period change has been extracted, and the periodic change caused by the light traveling time effect has a period of 42.2 years. The residuals are presented in the lower panel.

Table 1
The 412 Available pe/CCD Times of Light Maximum of DY Pegasi

JD.Hel. 2400000+	Detector	Epoch	$(O - C)$	Ref.
32751.8884	pe	−75761	−0.0042	1
32751.9613	pe	−75760	−0.0042	1
32752.9092	pe	−75747	−0.0044	1
34661.3915	pe	−49577	−0.0041	2
34661.4644	pe	−49576	−0.0042	2

Notes. The equation $\mathrm{HJD_{Max}} = 2438276.8643$ days + $0.07292633E$ days was used.

References. (1) Iriarte 1952; (2) Masani & Broglia 1954; (3) Detre & Chang 1960; (4) Hardie & Geilker 1958; (5) Broglia 1961; (6) Mahdy & Szeidl 1980; (7) Karetnikov & Medvedev 1964; (8) Fitch et al. 1966; (9) Warner & Nather 1972; (10) Geyer & Hoffman 1974; (11) Heiser 1976; (12) Quigley & Africano 1979; (13) Jiang & Zhao 1982; (14) Meylan et al. 1986; (15) Hobert et al. 1985; (16) Mahdy 1987; (17) Rodríguez et al. 1990; (18) Wilson et al. 1998; (19) Hintz et al. 2004; (20) Van Cauteren & Wils 2000; (21) Fu et al. 2009; (22) Agerer & Hübscher 1996; (23) Agerer et al. 1999; (24) Blake et al. 2000; (25) Agerer & Hübscher 1998; (26) Agerer et al. 2001; (27) Agerer & Hübscher 2002; (28) Derekas et al. 2003; (29) Agerer & Hübscher 2003; (30) Hübscher et al. 2005; (31) Hübscher et al. 2006; (32) Hübscher et al. 2009a; (33) Hübscher & Walter 2007; (34) Hübscher 2007; (35) Hübscher et al. 2009b; (36) Derekas et al. 2009; (37) Hübscher et al. 2008; (38) Wils et al. 2009; (39) present paper. The data with "*" are not used in the analysis because of large error.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

where T_0 is the initial epoch and P_0 is the pulsation period. In this paper, we set $T_0 = 2438276.8643$ and $P_0 = 0.07292633$ day. The $O - C$ values calculated with the initial ephemeris are listed in Table 1 and displayed in Figure 1. δT_0 and δP_0 are the correction values. β is the linear change of the pulsation period (day cycle^{-1}). Equation (3) was first given by Irwin (1952), where $A = a \sin i / c$, it is the projected semimajor axis given in days, e is the eccentricity, ν is the true anomaly, ω is the longitude of the periastron passage in the plane of the orbit, and E^* is the eccentric anomaly.

Table 2
The Pulsating and Orbital Elements of DY Pegasi

Element	Value
T_0[cor]	$2438276.86149 \pm 0.00013$
P_0[cor](days)	$0^{d}0729263444 \pm 0^{d}0000000028$
β(day cycle^{-1})	$(-6.59 \pm 0.38) \times 10^{-13}$
A(days)	0.00147 ± 0.00020
$a_1 \sin i$(AU)	0.254 ± 0.034
e	0.65 ± 0.10
ω	$180^{\circ}.7 \pm 10^{\circ}.3$
P_B(days)	15414.5 ± 548.8
T	2454074.1 ± 233.3

The Kepler equation gives the connection between E^* and the mean anomaly M:

$$M = E^* - e \sin E^* \tag{4}$$

and

$$M = \frac{2\pi}{P_B}(t - T), \tag{5}$$

where P_B is the orbital period of the binary system, t is the time of light maximum, and T is the time of passage through the periastron.

Equation (4) is a transcendental equation. So we give the E^* as a Bessel series in e instead:

$$E^* = M + \sum_{n=1}^{\infty} \frac{2}{n} J_n(ne) \sin(nM), \tag{6}$$

where

$$J_n(ne) = \sum_{k=0}^{\infty} (-1)^k \frac{1}{k!\Gamma(n+k+1)} \left(\frac{ne}{2}\right)^{n+2k}. \tag{7}$$

Table 2 lists the results of the nonlinear fit by the Levenberg–Marquardt method. The solid lines in Figures 1 and 2 are plotted with the parameters given in Table 2.

4. DISCUSSION

From the 62 years photometric observations, we obtained the orbital period $P_B = 15414.5 \pm 548.8$ days $= 42.2 \pm 1.5$ yr,

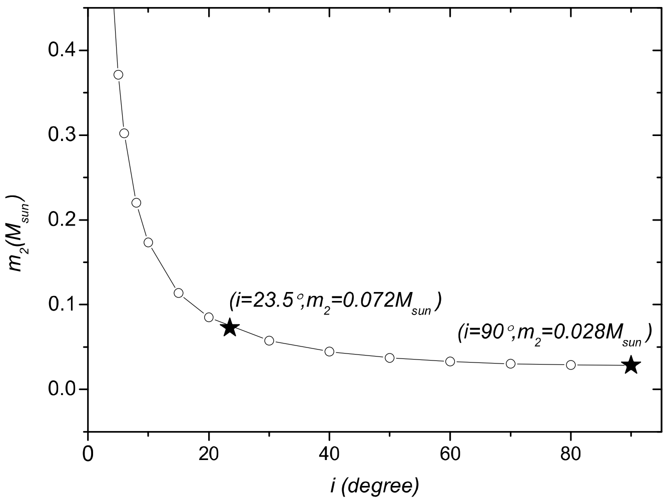

Figure 3. Relations between the orbital inclination i and the mass of the companion m_2. The companion should be a brown dwarf when $i \geqslant 23^\circ\!.5$.

which is shorter than that obtained by Fu et al. (2009). Hintz et al. (2004) made a thorough investigation of DY Pegasi and concluded the mass of the star to be $m_1 = 1.54\,M_\odot$. Using the mass function, we could obtain the mass of the companion m_2. The relations between the orbital inclination i and the mass of the companion m_2 are plotted in Figure 3. Considering the mass of a brown dwarf in theory is from $0.013\,M_\odot$ to $0.072\,M_\odot$, when the orbital inclination is larger than $23^\circ\!.5$, the companion should be a brown dwarf. If the inclination is random distribution, the possibility is 73.8%.

The orbital motion also can result in the periodic change of the mean radial velocity of the star. The radial velocity of DY Pegasi was first investigated by Bidelman (1947) and the mean radial velocity of about -25 km s^{-1} was given from only nine spectrograms. Recent similar work was done by Meylan et al. (1986) and Wilson et al. (1998), and radial velocities of -25.3 km s^{-1} and -21.5 km s^{-1} were determined, respectively. It seems that the values of the radial velocity really change in some way, but only three data are not enough to support an accurate research. Assuming that our orbital period is accurate, the orbital element K is estimated to be about 0.23 km s^{-1}. This value is so small that more accurate spectroscopic observations are needed to check the values of the orbital elements.

Previous authors have estimated the decreasing rate of the period of DY Pegasi with a parabolic fit. However, the result may be influenced by the other component existing in the $O - C$ diagram. We determined a decrease of the period at a rate of -6.59×10^{-13} days cycle^{-1}, or -9.04×10^{-12} days day^{-1}. This period change is less than the value obtained by Hintz et al. (2004). But it is better to be described with a 42.2 yr orbital period of the system. Of course, considering that the period changes predicted by evolution models should be positive, the possibility that the decreasing change could just be a part of a periodic change with a longer period cannot be ruled out (Fu et al. 2009).

5. CONCLUSION

We collected all the pe/CCD times of light maximum covering 62 years and studied the behavior of the pulsate period of DY Pegasi with the classical $O - C$ method. The variations of the period can be described by a secular decrease of the period at a rate of $dP/dt = -9.04 \times 10^{-12}$ days day^{-1}, and a perturbation from a companion star in an eccentric orbit with a period of 42.2 yr causing a light traveling time effect semi-amplitude of 0.00147 day. Assuming the mass of DY Pegasi was $1.54\,M_\odot$, we obtained the mass of the companion from $0.028\,M_\odot (i = 90^\circ)$ to $0.173\,M_\odot$ $(i = 10^\circ)$. This means that the companion is probably a brown dwarf. In order to confirm the existence of the companion, more precise photometric monitoring and spectroscopic observations are needed in the future.

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REFERENCES

Agerer, F., Dahm, M., & Hübscher, J. 1999, IBVS, 4712, 1
Agerer, F., Dahm, M., & Hübscher, J. 2001, IBVS, 5017, 1
Agerer, F., & Hübscher, J. 1996, IBVS, 4382, 1
Agerer, F., & Hübscher, J. 1998, IBVS, 4606, 1
Agerer, F., & Hübscher, J. 2002, IBVS, 5296, 1
Agerer, F., & Hübscher, J. 2003, IBVS, 5485, 1
Bidelman, W. P. 1947, ApJ, 106, 135
Blake, R. M., Khosravani, H., & Delaney, P. A. 2000, JRASC, 94, 124
Breger, M., & Pamyatnykh, A. A. 1998, A&A, 332, 958
Broglia, P. 1961, Mem. Soc. Astron. Ital., 32, 7
Derekas, A., et al. 2003, A&A, 402, 733
Derekas, A., et al. 2009, MNRAS, 394, 995
Detre, L., & Chang, Y. C. 1960, Acta Astron. Sin., 8, 50
Fauvaud, S., et al. 2006, A&A, 451, 999
Fitch, W. S., Wisniewski, W. Z., & Johnson, H. L. 1966, Commun. Lunar Planet. Lab., 5, 71
Fu, J. N., & Sterken, C. 2003, A&A, 405, 685
Fu, J. N., et al. 2008, AJ, 135, 1958
Fu, J. N., et al. 2009, PASP, 121, 251
Garrido, R., & Rodríguez, E. 1996, MNRAS, 281, 696
Geyer, E. H., & Hoffman, M. 1974, IBVS, 936
Grigorevski, V. M., & Mandel, O. E. 1960, Perem. Zvezdy, 13, 190
Hardie, R. H., & Geilker, C. D. 1958, ApJ, 127, 606
Heiser, E. 1976, Sterne Weltraum, 15, 166
Hintz, E. G., Joner, M. D., Ivanushkina, M., & Pilachowski, C. A. 2004, PASP, 116, 543
Hobert, M. A., Quintero, A., Pani, A., Peniche, R., & Peña, J. H. 1985, IBVS, 2816
Hübscher, J. 2007, IBVS, 5802, 1
Hübscher, J., Paschke, A., & Walter, F. 2005, IBVS, 5657, 1
Hübscher, J., Paschke, A., & Walter, F. 2006, IBVS, 5731, 1
Hübscher, J., Steinbach, H.-M., & Walter, F. 2008, IBVS, 5830, 1
Hübscher, J., Steinbach, H.-M., & Walter, F. 2009a, IBVS, 5874, 1
Hübscher, J., Steinbach, H.-M., & Walter, F. 2009b, IBVS, 5889, 1
Hübscher, J., & Walter, F. 2007, IBVS, 5761, 1
Iriarte, B. 1952, ApJ, 116, 382
Irwin, J. B. 1952, ApJ, 116, 211
Jiang, S., & Zhao, N. 1982, Acta Astrophys. Sin., 2, 49
Karetnikov, V. G., & Medvedev, Y. A. 1964, Perem. Zvezdy, 15, 268
Klingenberg, G., Dvorak, S. W., & Robertson, C. W. 2006, IBVS, 5701, 1
Kozar, T. 1980, IBVS, 1834, 1
Mahdy, H. A. 1987, IBVS, 3055, 1
Mahdy, H. A., & Szeidl, B. 1980, Commun. Konkoly Obs., 74, 1
Masani, A., & Broglia, P. 1954, Mem. Soc. Astron. Ital., 25, 431
Meylan, G., Burki, G., Rufener, F., Mayor, M., Burnet, M., & Ischi, E. 1986, A&AS, 64, 25
Morgenroth, O. 1934, Astron. Nachr., 252, 389
Paparó, M., Szeidl, B., & Mahdy, H. A. 1988, AP&SS, 149, 73
Peña, J. H., & Peniche, R. 1986, A&A, 166, 211

Quigley, R., & Africano, J. 1979, PASP, 92, 230
Rodríguez, E., & Breger, M. 2001, A&A, 366, 178
Rodríguez, E., López de Coca, P., Costa, V., & Martín, S. 1995, A&A, 299, 108
Rodríguez, E., Rolland, A., & Lopez De Coca, P. 1990, IBVS, 3428, 1
Soloviev, A. V. 1938, Tadjik Obs. Circ., 37
Soloviev, A. V. 1940, Tadjik Obs. Circ., 44
Van Cauteren, P., & Wils, P. 2000, IBVS, 4872, 1
Warner, B., & Nather, R. E. 1972, MNRAS, 156, 315
Wils, P., Kleidis, S., & Hambsch, F.-J. 2009, IBVS, 5878, 1
Wilson, W. J. F., Milone, E. F., Fry, D. J. I., & Van Leeuwen, J. 1998, PASP, 110, 433