The Astrophysical Journal, 703:109–113, 2009 September 20
doi:10.1088/0004-637X/703/1/109

EVIDENCE OF A BROWN DWARF IN THE ECLIPSING DWARF NOVA Z CHAMAELEONIS

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Received 2009 February 19; accepted 2009 June 9; published 2009 August 26

ABSTRACT

We presented three new CCD observations of light minima of Z Chamaeleonis. All 187 available times of light minimum including 37 photographic data are compiled, and a new orbital period analysis is made by means of the standard $O - C$ technique. The $O - C$ diagram of Z Chamaeleonis presents a cyclical periodic change of ~ 32.57 yr with a high significance level. We attempted to apply two plausible mechanisms (i.e., Applegate's mechanism and light travel-time effect) to explain the cyclical variations of orbital period shown in the O–C diagram. Although the previous works suggested that solar-type magnetic cycles in the red dwarf are the best explanation, the analysis of Applegate's mechanism in this paper presents a negative result. Accordingly, a light travel-time effect is proposed, and a brown dwarf as a tertiary component orbiting around dwarf nova Z Chamaeleonis is derived with a significance level of $\gtrsim$ 81.6%, which may be a plausible explanation of the periodic variation in the systemic velocity of Z Chamaeleonis in superoutburst.

Key words: binaries: eclipsing – novae, cataclysmic variables – stars: individual (Z Chamaeleonis)

Online-only material: machine-readable table

1. INTRODUCTION

Z Chamaeleonis is a dwarf nova and classified as a member of the SU Ursae Majoris subclass (Haefner et al. 1979), which means that it has both normal outbursts and superoutbursts (e.g., Warner 1995). Mumford (1969, 1971) has shown that Z Chamaeleonis is an eclipsing binary with an orbital period of 107 minutes, fading from $V \sim 15.5$ to $V \sim 17.3$ in eclipse during quiescence. Optical photometry of Z Chamaeleonis (Warner 1974; Bailey 1979) indicates that eclipses of the white dwarf, the accretion disk, and the bright spot are all distinctly presented in the light curve. This provides the best opportunity for studying its geometric structure and system parameters (Vogt 1982; Wood et al. 1986; Wade & Horne 1988). However, the masses of both components determined in the photometric eclipse analysis published by Wood et al. (1986) are obviously different from the traditional spectroscopic solutions derived by Vogt (1982) and Wade & Horne (1988). Thus, there is still not a consistent model for Z Chamaeleonis.

The detailed eclipse properties shown in the light curve of Z Chamaeleonis allow for precise measurements of the time of mid-eclipse and orbital period. Since eclipse provides a fiducial mark in time with high precision and the time of the white dwarf eclipse of Z Chamaeleonis can be obtained by measuring its mid-ingress and mid-egress time (Wood et al. 1985), the deep and multi-component eclipse presented by Wood et al. (1986) indicates that the variations in the orbital period can correctly reflect the secular evolution. This means that Z Chamaeleonis is a particularly important object, since the white dwarf eclipses in other dwarf novae (e.g., U Gem Arnold et al. 1976) cannot be definitely separated from the eclipsing light curves. In early O–C analysis, Cook & Warner (1981) and Wood et al. (1986) suggested that the orbital period of Z Chamaeleonis is increasing. But recent works (Van Amerongen et al. 1990; Robinson et al. 1995; Baptista et al. 2002) imply that the orbital period of Z Chameleonis may present cyclical changes with period $\sim$ 28 yr, which is explained by the effect of a solar-type magnetic activity cycle in the secondary star.

In this paper, three new data from our observations are presented in Section 2. Section 3 deals with the O–C analysis for Z Chamaeleonis. Finally, the discussions of the possible mechanisms for orbital period changes are presented in Section 4.

2. OBSERVATION OF TIMES OF LIGHT MINIMUM

Three new times of light minimum are obtained from our CCD photometric observations using a Photometrics CH250 CCD camera system with a PM512 chip attached to the 0.6 m Helen Sawyer Hogg telescope (HSH) at Complejo Astronomico El Leoncito (CASLEO), San Juan, Argentina. They are listed in Table 1. The first and second CCD photometric observations of Z Chamaeleonis were carried out on 2008 April 5 and 9, respectively, and the final observation on 2008 December 2. The first photometry was in the R filter, and the other two in white light. Two nearby stars which have similar brightness in the same viewing field of the telescope, were chosen as the comparison star and the check star. All images were reduced by using PHOT (measure magnitudes for a list of stars) in the aperture photometry package of IRAF. Three CCD times of light minimum were derived by using a parabolic fitting method to the part of the white dwarf eclipse.

The CCD or photoelectric data without given error are arbitrarily adopted with default errors $0\overset{\mathrm{d}}{.}0001$ which is higher than Baptista et al. (2002), since most recent eclipsing times obtained from CCD observations have only four significant figures. In addition, the 37 photographic data have errors $0\overset{\mathrm{d}}{.}001$. The collected times of light minimum were checked again because some data were obtained many years ago. Some identical times of light minimum have small differences as they were observed in many different observatories or observed in different filters. In this case, the average value should be reliable. Moreover, Honey et al. (1988) and Van

Table 1
The Times of Light Minimum for the Dwarf Nova Z Chamaeleonis

JD.Hel. 2400000+	Type	Error	Method	E (cycle)	$(O-C)^d$	Ref.
43575.280131+	pri		pe	44438	−0.00066	1
43575.354664+	pri		pe	44439	−0.00063	1
43576.323125+	pri		pe	44452	−0.00066	1
44335.321965+	pri		pe	54640	−0.00065	2
44336.290497+	pri		pe	54653	−0.00061	2
44643.525632+	pri		pe	58777	−0.00057	2
45762.654267+	pri		pe	73799	−0.00036	1
46411.543233+	pri		pe	82509	−0.00027	3
46415.417503+	pri		pe	82561	+0.000043	3
46415.491673+	pri		pe	82562	−0.00029	3
46415.566253+	pri		pe	82563	−0.00021	3
46416.460853+	pri		pe	82575	+0.00040	3
46416.534603+	pri		pe	82576	−0.00035	3
46738.744101+	pri		pe	86901	−0.00031	1
48714.01955+	pri	.00002	ccd	113415	+0.00080	4
54561.615200N	pri	.0005	ccd	191907	−0.00230	5
54565.713400N	pri	.0005	ccd	191962	−0.00160	5
54802.621400R	pri	.0005	ccd	195142	−0.00140	5

Notes.
+ The converted data from HJED or BJDD data.
N N filter observation.
R R filter observation.
Reference. (1) Van Amerongen et al. 1990; (2) Warner & O'Donoghue 1988; (3) Honey et al. 1988; (4) Robinson et al. 1995; (5) This paper.
(This table is available in a machine-readable form in the online journal.)

Amerongen et al. (1990) reported their 80 eclipse times in Heliocentric Julian Ephemeris Dates (HJED), which correspond to ET (i.e., terrestrial dynamical time (TDT)) time system. In addition, Robinson et al. (1995) presented an eclipse time in Barycentric Julian Dynamical Data (BJDD), which also corresponds to TDT. Baptista et al. (2002) pointed out that for Z Chamaeleonis the difference between Heliocentric Julian Dates (HJD) and BJDD is smaller than 1 s, because it is close to the ecliptic pole. Thus, we converted HJED and BJDD to HJD, which corresponds to coordinated Universal time (UTC) by using the average formula (i.e., HJD = HJED − 0.000627) given by Wood et al. (1989). Although UTC is not a uniform time system, it is an older time system than TDT and the difference between both time systems is less than one minute in the last century (e.g., dickey 1995; meeus 1998). Therefore, in order to match with the oldest data (presented in HJD), we chose the HJD time system for our O–C analysis. In fact, there are only 15 data listed in Table 1 from 1978 March to 1992 April, which needed to be converted. This means that the average formula of Wood et al. (1989) is accurate enough. The other data are directly observed in the HJD system.

3. ANALYSIS OF ORBITAL PERIOD CHANGES

The ephemeris derived by Baptista et al. (2002) is used to calculate all 187 O–C values of Z Chamaeleonis, and the new linear fit is made. The new epochs and average orbital period of Z Chamaeleonis were calculated as,

$$T_{\min} = \mathrm{HJD}\ 2440264.68107(2) + 0\overset{d}{.}0744992962(2)E, \quad (1)$$

with variance $\sigma_1 = 8\overset{d}{.}91 \times 10^{-4}$. Based on Equation (1), the calculated O–C values are listed in Column 6 of Table 1. The three new eclipse times we obtained reflect a possible cyclical departure in the orbital period of Z Chamaeleonis. Although our three data points cannot obey well the variational trend predicted by Baptista et al. (2002), the fit of simultaneous quadratic-plus-sinusoidal ephemeris only give weak evidence to present the secular changes in the orbital period of Z Chamaeleonis. Therefore, we used a linear-plus-sinusoidal ephemeris to fit the data as Baptista et al. (2002) did. The weights of data points are calculated from the uncertainties of the mid-eclipse times. The least-square solution leads to

Table 2
The Fitting Parameters of the Dwarf Nova Z Chamaeleonis

$(O-C)_n$	$P_{\rm cyc}$(yr)	λ	$\sigma(d)$	χ^2
$(O-C)_1$	26.51(±3.8)	$F(3, 182) = 54.7$	0.00065	5.4
$(O-C)_2$	32.57(±0.19)	$F(3, 145) = 696.3$	0.00023	3.5

$$\begin{aligned}(O-C)_1 = {} & 5\overset{d}{.}1(\pm0\overset{d}{.}1)\times10^{-4} - 3\overset{d}{.}9(\pm0\overset{d}{.}2)\times10^{-9}E \\ & + 8\overset{d}{.}8(\pm0\overset{d}{.}1)\times10^{-4}\sin[0.0028(\pm0.0004)^\circ E \\ & + 113\overset{\circ}{.}7(\pm0\overset{\circ}{.}8)]. \end{aligned} \quad (2)$$

The fitting parameters are listed in Table 2. Since the residuals of the paragraphic data present large scatters displayed in the bottom panel of Figure 1(a), we attempted to abandon all 37 low precision data in the fit and the resulting O–C diagram is shown in Figure 1(b). The new fitting formula can be obtained as

$$\begin{aligned}(O-C)_2 = {} & 1\overset{d}{.}17(\pm0\overset{d}{.}02)\times10^{-3} - 1\overset{d}{.}15(\pm0\overset{d}{.}02) \\ & \times 10^{-8}E + 1\overset{d}{.}16(\pm0\overset{d}{.}4)\times10^{-3}\sin[0.002256 \\ & \times(\pm0.000013)^\circ \times E + 158\overset{\circ}{.}5(\pm0\overset{\circ}{.}6)]. \end{aligned} \quad (3)$$

The residual of this fit is almost one order of magnitude lower than the fit for all data. Since Baptista et al. (2002) used the F-test proposed by Pringle (1975) to measure the significance level for the linear-plus-sinusoidal fit, we recalculated the statistic system parameter λ for Equations (2) and (3) listed in Table 2, which indicate that both fits are significant well above the 99.99% level. Moreover, for describing the goodness-of-fit of Equations (2) and (3), we also calculated the χ^2 values of both fits, which are presented in Table 2. Although the fitting χ^2 is larger than unity, the final solution is still better than that of Baptista et al. (2002). Since the χ^2 for Equation (3) is lower than that for Equation (2), the best fit of the O–C diagram for Z Chamaeleonis is that the modulation period is ~32.57(±0.19) yr and the amplitude of the periodic changes are a little larger than the results derived by Baptista et al. (2002).

In order to test that the $(O-C)$ variations shown in Figure 1 obeys a strictly periodic change in the timings, we divided the $(O-C)_2$ diagram into two sections with nearly the same data span (~16 yr), and fit both portions as Baptista et al. (2002) did. Since we only considered the cyclical period changes in the $(O-C)$ diagram, the linear term in Equation (3) was removed and a pure oscillation presented in Figure 2. The three sinusoidal curves shown in Figure 2 are nearly completely overlapped, and their fitting parameters are listed in Table 3. The small differences in period and amplitude between both portions are $\simeq$ 0.4 yr and $\simeq$ 6 s, respectively, and both periods are similar to the best-fit period of 32.57(±0.19) yr, which indicates that the differences may be just from the systemic errors and fitting errors. Therefore, we assumed that the strictly periodic oscillation in Figure 1 and Figure 2 should be reasonable. Although a sinusoidal fit for the complete $(O-C)_3$ data set presents a period ~33.6 yr, which is a little larger than the two

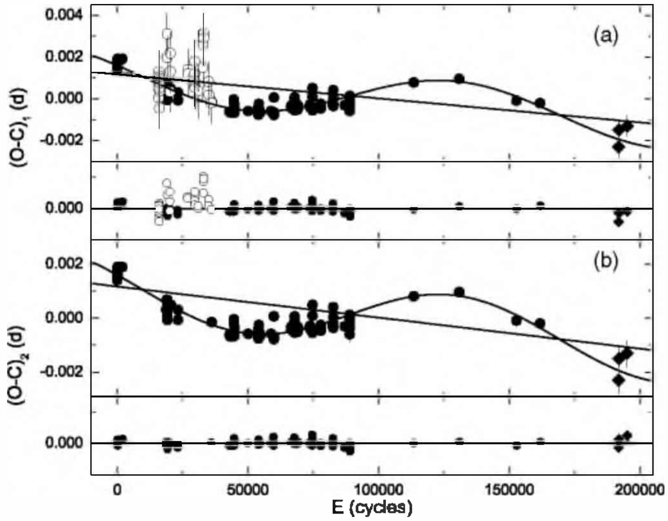

Figure 1. O–C values calculated with Equations (2) and (3) vs. the cycles are plotted in (a) and (b) planes and correspond to the fits of all data and high precision data, respectively. The solid line is the best fit for O–C values of Z Chamaeleonis. The 37 photographic data and the photoelectric or CCD data are plotted as open circles and solid circles, respectively. Our data are plotted as solid diamonds.

Table 3
The Separated Fits for Each Half of the Data

$(O-C)_n$	$P_{\rm cyc}$(yr)	$A(s)$	$\sigma(d)$	χ^2
the first half	32.0	96.8	0.00019	3.5
the second half	32.4	90.7	0.00033	8.3
$(O-C)_3$	33.6	95.0	0.00022	4.4

periods obtained from the separated fits, a similarity between the two periods ensures the existence of a strict period in the O–C diagram of Z Chamaeleonis.

4. DISCUSSION

4.1. Applegate's Mechanism

Van Amerongen et al. (1990) attempted to use a third-degree polynomial ephemeris to fit O–C values for Z Chamaeleonis and found that during the last few years the orbital period is decreasing. Although Figure 7 in Robinson et al. (1995) shows that there are short-term departures (±15 s) from the quadratic ephemeris on timescales near 10 yr, they never preformed any of the available analysis for these variations. The previous O–C analysis (Baptista et al. 2002) confirmed the prior assumption that the orbital period should be cyclical changes which is attributed to a solar-type magnetic activity cycle in the secondary star. But they did not show a calculation of energy required to produce this periodic oscillation. Usually the required energy is too large and limits this mechanism's ability to explain the cyclic variations of the orbital period (Qian et al. 2007, 2008). Applegate (1992) derived a relationship between the amplitude of orbital period changes P and the variation of quadrupole momentum $\triangle Q$ as

$$\frac{\triangle P}{P} = -9\left(\frac{R_2}{a}\right)^2 \frac{\triangle Q}{M_2 {R_2}^2}, \quad (4)$$

where R_2 and a are the radius of secondary star and the binary separation, respectively. $\triangle Q$ can be calculated to be $-4.4(\pm 0.5) \times 10^{46}$ g cm^2 by using the system parameters of

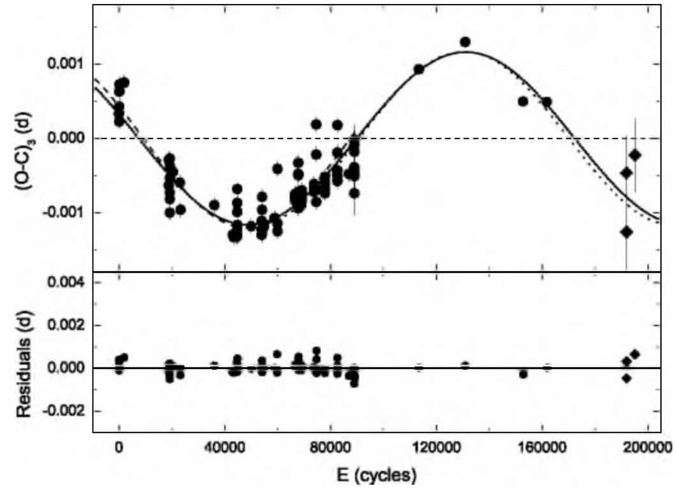

Figure 2. O–C values after removing the linear term of Equation (3) vs. the cycles are plotted in the top plane. The newest data are plotted as solid diamond. The solid line is the best-fit curve for the complete data, and the dashed curve and the dotted curve are the best fit for the data on the first half and the last half of the data, respectively. The residuals of sinusoidal fit for the complete data are shown in the lower panel.

Wade & Horne (1988). The red dwarf may be a fully convective star, and even a massive brown dwarf due to its extremely low mass (0.081 $M_\odot$; Wood et al. 1986) which is near the hydrogen burning limit. The energies, $\triangle E$, required to cause the angular momentum transfer, $\triangle J$, between shell and core, versus each different shell mass, M_s, are plotted in Figure 3. The lowest required energy $\triangle E_{\rm min}$ is 7.25×10^{40} erg at $M_s \simeq 0.093\, M_\odot$. Since the spectral type of the secondary star of Z Chamaeleonis is dM5.5 based on the analysis of the ratio of TiO band strengths (Wade & Horne 1988), the total radiant energy E_0 in a complete variation period 32.57 yr can be estimated to be $\sim 7.22 \times 10^{39}$ erg, which is the maximum energy offered by the luminosity variation of the dM5.5 V-type red dwarf. Accordingly, $\triangle E_{\rm min}$ is over one order of magnitude higher than the E_0, which indicates that Applegate's mechanism cannot be a reasonable explanation for the cyclic variations. Moreover, an important assumption cannot be neglected, i.e., the energy offered by the brightness modulation of Z Chamaeleonis with an amplitude of $\triangle m_v \simeq 0.16$ (Ak et al. 2001) is far smaller than E_0. Since the ratio $E_0/\triangle E_{\rm min} \sim 0.09$ is so low that solar-type magnetic cycle may have difficulty explaining the observed oscillation in the orbital period.

4.2. Light Travel-Time Effect

A notable trend in the O–C diagram of Z Chamaeleonis is a ∼32.57 yr quasi-period variation which cannot be well interpreted by Applegate's mechanism. Therefore, we attempted to explain it with a light travel-time effect due to perturbations from a tertiary component (Irwin 1952; Borkovits & Hegedues 1996). The excellent sinusoidal fits, shown in Figures 1 and 2, suggest that the orbital eccentricity of the third body should be small. The projected distance $a' \sin(i) = 0.2(\pm 0.07)$ AU, which is the separation from the binary pair to the mass center of this triple system, can be calculated by the amplitude of the sinusoidal fit. The mass function of the third component $f(m_3)$, can be estimated by the formula,

$$f(m_3) = \frac{4\pi^2}{GP_3^2} \times (a' \sin(i))^3, \quad (5)$$

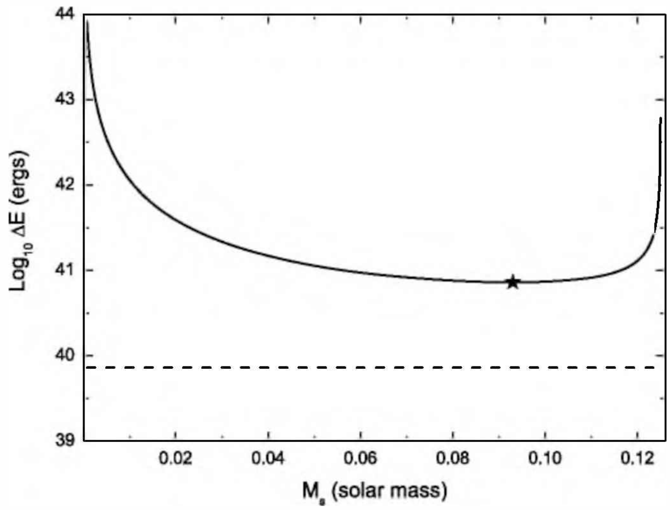

Figure 3. Plot of the correlation between the energy required to produce the orbital period oscillation of Z Chamaeleonis by using Applegate's mechanism and the assumed different shell masses of the fully convective red dwarf are presented as a solid line. The star denotes the minimum required energy, and the dashed line refers to the total radiant energy of the red dwarf over the whole oscillation period ∼ 33.34 yr.

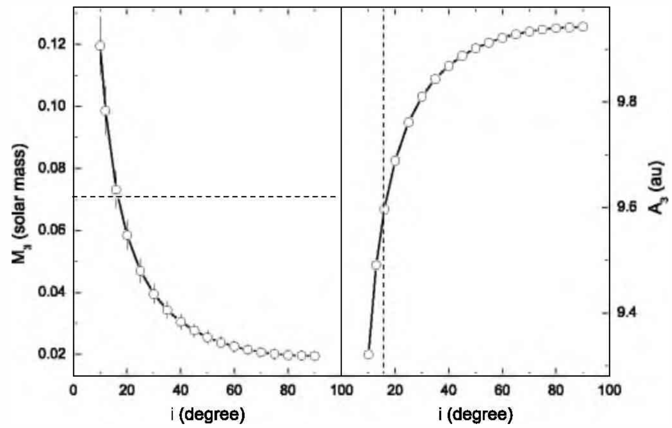

Figure 4. Both correlations $M_3 - i$ and $A_3 - i$ are presented in the left plane and the right plane, respectively. And the two dashed lines in the left and right planes denote the upper limit of the masses of brown dwarf ($\sim 0.071\ M_\odot$), and the corresponding inclination $i = 16\overset{\circ}{.}6$, respectively.

where P_3 is the period of the third-body and i is the inclination of the third body orbit. Assuming a combined mass of $0.84(\pm0.09)\ M_\odot + 0.125(\pm0.014)\ M_\odot$ for the eclipsing pair of Z Chamaeleonis (Wade & Horne 1988), $f(m_3) = 7.6(\pm0.8) \times 10^{-6}\ M_\odot$ is derived and the relationship between the mass of the third body M_3 and its orbital inclination i is displayed in Figure 4. The third body in this binary system should be a brown dwarf as long as $i > 16\overset{\circ}{.}6$, which implies that it is a brown dwarf with a confidence level $\gtrsim 81.6\%$ based on the inclination. Assuming the orbit of the third body almost coplanar to the dwarf nova Z Chamaeleonis with the inclination $i \approx 81\overset{\circ}{.}78$ (Wade & Horne 1988), the third body should be a low mass brown dwarf with a mass of $M_3 \sim 0.02\ M_\odot$ which is ∼ 20 times larger than that of Jupiter, and its distance from the binary system shown in the right plane of Figure 4 is ∼ 9.9 AU, nearly 2.9×10^3 times the binary separation. Thus this tertiary component could have survive the previous evolution of the system when it was a wider binary, possibly with a red giant component. A third body with a mass as small as $0.01\ M_\odot$ at a distance greater than 8 AU would be enough to account for the oscillation of mid-eclipse time proposed by Robinson et al. (1995). Therefore, the brown dwarf we derived is sufficient to cause the observed cyclical changes.

5. CONCLUSION

All 187 available times of light minimum covering 39 yr are compiled and a new O–C diagram of Z Chamaeleonis is obtained. A sinusoidal variation with ∼ 32.57 yr period is discovered in the O–C analysis. Two plausible mechanisms via Applegate's mechanism and light travel-time effect are discussed for explaining the cyclical period changes shown in O–C diagram. The former mechanism is derived with negative result since the required energy is too high. Based on the analysis of the light travel-time effect, a brown-dwarf star as a third component of the system may be explored with a significance level of $\gtrsim 81.6\%$. Especially, when the inclination of the third body is high enough, its mass approach to the lower limit of a brown dwarf's mass $0.013\ M_\odot$.

Honey et al. (1988) has found a periodic variation in the systemic velocity when Z Chamaeleonis is in superoutburst. They attributed this variation to an eccentric, precessing disk which is tidally distorted by the secondary star. However, compared with both of the components, the accretion disk around the white dwarf only has very low mass (average value $\sim 10^{-10}\ M_\odot$ (Warner 1995)). This tiny dynamic effect caused by the disk is insufficient to wobble the mass center of the whole binary. Thus we regarded that this variation is probably just the disturbance of a remote brown dwarf. However, since the result of Honey et al. (1988) did not cover a complete modulated period, further studies on the changing behavior of the systemic velocity in Z Chamaeleonis are needed to confirm this assumption.

This work was partly Supported by Special Foundation of President of The Chinese Academy of Sciences and West Light Foundation of The Chinese Academy of Sciences, Yunnan Natural Science Foundation (2008CD157), the Yunnan Natural Science Foundation (No. 2005A0059M) and Chinese Natural Science (No.10573032, No. 10573013 and No.10433030). CCD photometric observations of Z Chamaeleonis were obtained with the 0.6-m Helen Sawyer Hogg telescope at CASLEO, San Juan, Argentina. We thank the referee very much for the helpful comments and suggestions that helped to improve this paper greatly.

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