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The semi-detached binary system IU Per and its intrinsic oscillation *

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Abstract We present a long-term time-resolved photometry of the short-period eclipsing binary IU Per. It confirms the intrinsic δ Scuti-like pulsation of the system reported by Kim et al. . With the obtained data, an orbital period study and an eclipsing light curve synthesis based on the Wilson-Devinney method were carried out. The photometric solution reveals a semi-detached configuration with the less-massive component filling its own Roche-lobe. By subtracting the eclipsing light changes from the data, we obtained the pure pulsating light curve of the mass-accreting primary component. A Fourier analysis reveals four pulsation modes with confidence larger than 99%. A mode identification based on the results of the photometric solution was made. It suggests that the star may be in radial pulsation with a fundamental period of about 0.0628 d. A brief discussion concerning the evolutionary status and the pulsation nature is finally given.

Key words: stars: binaries: eclipsing — stars: oscillations — stars: individual (IU Per)

1 INTRODUCTION

Pulsating stars in eclipsing binary systems are of peculiar interest for the theoretical study of stellar structure and evolution because binarity of these stars provides useful information about the components. In general, the physical parameters (mass, radius, luminosity etc.) of the stars in a binary system could be precisely determined based on photometric and spectroscopic observations. It enables one to definitely identify the pulsation modes and to compare the results with theoretical models in detail. The study of pulsating stars in eclipsing binaries will offer new and strict constraints for the theories. On the other hand, the asteroseismology study can provide more information about the interior structure of the pulsating component, which will help us to understand the influences of tidal forces and mass transfer among the interacting binaries.

The existence of stellar pulsation in eclipsing binaries has been noted since the early 1970s (Tempesti 1971; Broglia & Marin 1974; McInally & Austin 1977), but very few such objects were observed until 2000. It became a very attractive subject since the beginning of this century. Many efforts have been made in searching for pulsating stars in eclipsing binaries. A complete list of pulsating stars detected in eclipsing binary systems can be found in Soydugan et al. (2006). Among which, most of the discoveries were contributed by the Central Asian Network (Mkrtichian et al. 2002) and South Korea Network (Kim et al. 2002a,b) groups. Very recently, Pigulski & Michalska (2007) reported the discovery of 13 eclipsing binaries with pulsating stars from the ASAS-3 data. This announcement makes the count of pulsating eclipsing systems increase to about 40.

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The less-studied star IU Per (α_{2000} = 02: 59: 37, δ_{2000} = +43: 55.3) is very probably a new pulsating eclipsing binary system in the GCVS catalog; it is classified as an EA/SD type system with a spectral type of A4 (Samus 2004). With a period of 0.8570257 d (Kreiner 2004), it is one of the pulsating eclipsing systems with the shortest orbital period. A study of the long-term orbital period changes by Qian (2001) showed that the system is undergoing a continuous decrease in its period. This suggests very probable significant angular momentum loss if the star is a semi-detached system as predicted. The intrinsic pulsation upon the eclipsing light changes of IU Per was reported by Kim et al. (2005). Through a Fourier analysis, Kim et al. (2005) detected two pulsation frequencies of $f_1 = 42.103$ c/d and $f_2 = 45.806$ c/d. They concluded that IU Per could be an oscillating EA (oEA) star consisting of a δ Scuti like, multi-periodic pulsating mass-accreting component.

Because of the short orbital period, the predicted semi-detached configuration and the very probable multi-periodic oscillation, IU Per seems to be a very interesting object. However, very little is known about this star. The physical nature of the binary system and its intrinsic pulsation is still uncertain. In the 2006/07 observation seasons, we have observed this star for a long time and collected sufficient photometric data. We present the results of the observations in this paper, as well as a comprehensive study of the binary system and its intrinsic pulsation.

2 OBSERVATIONS AND DATA REDUCTION

The CCD photometric observations were carried out at the Xinglong Station of the National Astronomical Observatories (NAOC) from Nov. 03 to 15, 2007 by using the APM 50 cm telescope. The data were taken with a 1320×1320 CCD camera, giving a field size of 20.2 arcmin with a scale of 0.92 arcsec pixel^{-1}. A single Johnson V filter was used. Exposure times were set from 10 to 15 s according to the weather conditions. Useful data were collected on 9 nights. A total number of 8400 frames were obtained.

The preliminary processing of the CCD frames was performed with the standard routines of CCDPROC in the IRAF package. All frames were bias subtracted and flatfielded with averaged sky flats. Photometry was performed using the DAOPHOTII package (Stetson 1987, 1996). For the purpose of differential photometry, we first choose a number of relatively bright stars which were observed with good seeing in the program field as reference stars. Two stars, GSC0008–743 (α_{2000} =03: 00: 20, δ_{2000} = +43: 55: 25, $V = 11.36$, Kharchenko 2001) and GSC0008–949 (α_{2000} = 02: 59: 32, δ_{2000} = +43: 55: 55, $V = 11.88$, Kharchenko 2001), which have been used as comparison and check stars by Kim et al. (2005), were confirmed to be constant within 0.01 mag on every night. They were finally also employed as the comparison and check stars for our observations. We then extracted the differential measurements of the target in each frame. The CCD photometric data tabulated in the form of HJD time vs. differential magnitude is presented as supplementary data in the Web version of this paper.

In addition to the CCD photometry, we have performed fast photometry with a 4-channel photoelectric photometer from Dec. 13 to 20 in 2006. The observation was done with the 85-cm reflector also located at the Xinglong station of NAOC. A single narrow-band b filter was used in data collection. We also chose the star GSC0008–949 as the comparison. Because of the bad weather, we only obtained useful data on 3 nights. These data will only be used for the detection of minimum times.

As an example of the time-series observations, we present single-night b and V band light curves in Figure 1. The b-band light curve was obtained photoelectrically on Dec. 14, 2006 and the V light curve was derived on Nov. 15, 2007 by CCD photometry. Inspecting the light curves, the short-term light variations in addition to the eclipsing light changes can be clearly seen. It confirms the discovery of Kim et al. (2005).

3 THE ECLIPSING BINARY SYSTEM

A total of 7 eclipses were recorded in our observations of IU Per. By using the K-W method (Kwee & van Woerden 1956), the epochs of these light minima were determined as given in Table 1. In addition, we have collected 16 further minimum times for the star from the literature (Hanzl 2001; Krajci 2005;

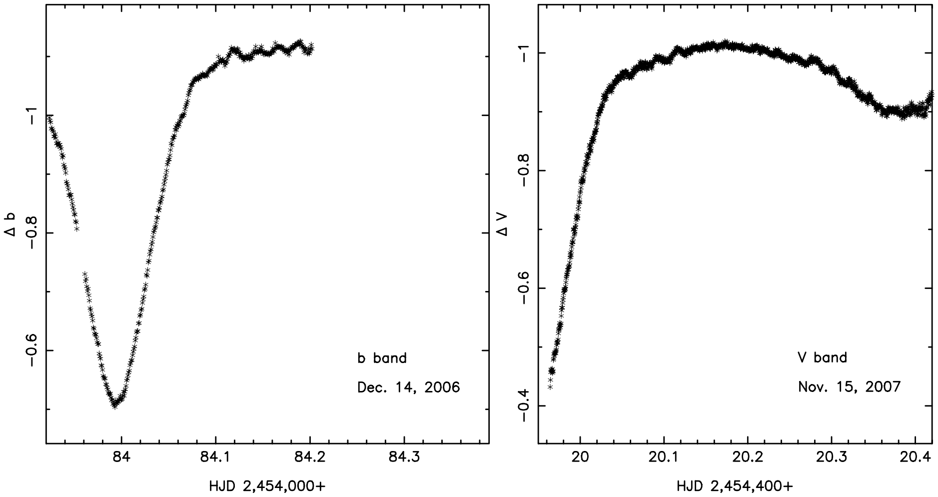

Fig. 1 Real-time *b* and *V*-band light curves of IU Per observed on Dec. 14, 2006 and Nov. 15, 2007, respectively.

Table 1 Photoelectric and CCD times of minima for IU Per and the residuals computed from the ephemerides (1) and (2).

HJD (2,400,000)	Epoch	$(O-C)1$ (d)	$(O-C)2$ (d)	Source
47847.4184	–7661.0	–0.0031	–0.0012	BAV-M 56
48567.3236	–6821.0	0.0008	0.0012	Hanzl 1994
51906.2983	–2925.0	0.0044	0.0024	Agerer & Hubscher 2002
52697.3303	–2002.0	0.0019	0.0005	Brat et al. 2007
52931.2940	–1729.0	–0.0023	–0.0035	Hubscher 2005
52937.3019	–1722.0	0.0064	0.0053	Hubscher 2005
53028.1419	–1616.0	0.0017	0.0007	Krajci 2005
53253.5389	–1353.0	0.0010	0.0003	Hubscher et al. 2005
53308.3821	–1289.0	–0.0054	–0.0061	Bakis et al. 2005
53350.3792	–1240.0	–0.0026	–0.0032	Brat et al. 2007
53361.5223	–1227.0	–0.0008	–0.0014	Zejda et al. 2006
53422.3731	–1156.0	0.0012	0.0007	Hubscher et al. 2005
53674.3375	–862.0	0.0001	0.0000	Hubscher et al. 2006
53705.6226	–825.5	0.0038	0.0038	Hubscher et al. 2006
53708.6168	–822.0	–0.0016	–0.0016	Dvorak 2006
54075.4244	–394.0	–0.0009	–0.0002	Brat et al. 2007
54083.1373	–385.0	–0.0012	–0.0006	present work
54083.9942	–384.0	–0.0013	–0.0007	present work
54089.9938	–377.0	–0.0009	–0.0003	present work
54409.2368	–4.5	0.0001	0.0014	present work
54410.0898	–3.5	–0.0039	–0.0026	present work
54411.3805	–2.0	0.0013	0.0026	present work
54413.0944	0.0	0.0011	0.0024	present work

Bakis 2005; Hubscher 2005; Hubscher et al. 2005; Dvorak 2006; Hubscher et al. 2006; Zejda et al. 2006), which were all detected through photoelectric or CCD photometry. They are all listed in Table 1. With a time span longer than 20 years, these data enable us to study the long-term period changes of the system.

By using the least square fitting method, the following linear and quadratic ephemerides were determined

$$\mathrm{Min.}I = \mathrm{HJD}2454413.0933(5) + 0^{\mathrm{d}}.85702543(20) \times E, \tag{1}$$

$$\mathrm{Min.}I = \mathrm{HJD}2454413.0920(7) + 0^{\mathrm{d}}.85702357(70) \times E - 2.53(92) \times 10^{-10} \times E^2. \tag{2}$$

The $(O - C)$ residual values for all the observed minimum times computed with respect to the ephemerides (1) and (2) were also given in Table 1. The period analysis gives a renewed orbital period obviously shorter than that given by Kreiner (2004). Meanwhile, it shows that the system seems to be undergoing a continuous period decrease with a rate of $dP/dE = -5.1 \times 10^{-10}\,\mathrm{cyc\,d}^{-1}$ or $dP/dt = -2.2 \times 10^{-7}\,\mathrm{d\,yr}^{-1}$. This supports the result of Qian (2001).

With the derived linear ephemeris (1), we computed the phases of all the measurements. The phased V band light curve was formed as shown in Figure 2. The general feature of the light curve is typical of EB rather than EA type as assigned in the GCVS (Samus 2004). The depths of the primary and secondary eclipse in the V band were measured to be 0.62 mag and 0.10 mag, respectively. With the V-band magnitude given for comparison, $V = 11.36$ mag, the magnitude of IU Per at the maximum light is calibrated to be about $V = 10.36$ mag.

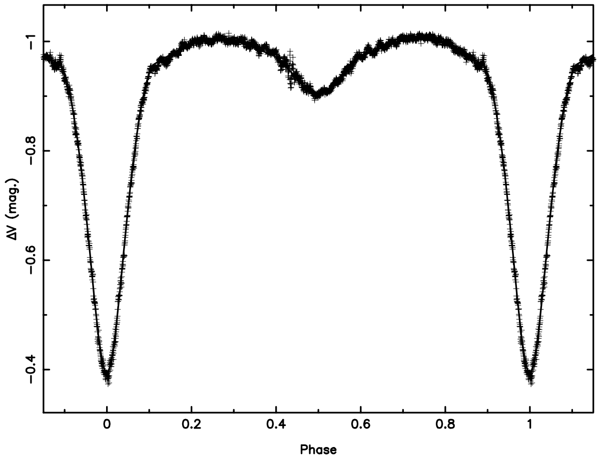

Fig. 2 IU Per: phased V-band light curve and the theoretical synthesis.

The V-band eclipsing light curve was then analyzed by using the 2003 version of the Wilson-Devinney (W-D, hereafter) code with the Kurucz atmospheres (Wilson & Devinney 1971; Wilson 1979, 1990; Kallrath et al. 1998). All the measurements were included in the computation of the photometric solution. A nonlinear limb-darkening law with the logarithmic form was applied in the light curve synthesis. Considering the probable close distance between the components, the effect of reflection has been taken into account.

In computing the photometric solution, the temperature of the primary star was set at 6450 K according to its spectral type of A4 through the calibration of Cox (2000). The initial bolometric (X_1, X_2, Y_1, Y_2) and monochromatic (x_1, y_1, x_2, y_2) limb-darkening coefficients of the components were taken from Van Hamme (1993). The gravity darkening exponents were set to be $g_1 = 1.0$ for the primary and $g_2 = 0.32$ for the secondary component according to Lucy (1967). The bolometric albedos were taken as $A_1 = 1.0$ and $A_2 = 0.5$ following Rucinski (1969).

Since there is no radial-velocity solution available for IU Per, the mass ratio $q = M_2/M_1$ (the most sensitive parameter for light curve synthesis) of the system is unknown. To search for an approximate mass ratio, we made a set of test solutions at the outset. The test solutions were computed at a series of assumed mass ratios with values ranging from 0.05 to 0.95. At each assumed mass ratio, the DC program started from mode 2 (detached configuration). After several iterations, a converged solution was reached for each assumed mass ratio. The results show that the most probable solution would be around $q = 0.275$. Starting from the solution at $q = 0.275$, we ran the DC code again and let the mass ratio be adjusted freely along with the other adjustable parameters. The final best-fitting solution was derived at $q = 0.2738$ as given in Table 2. The synthesis of the observed V-band light curve is shown in Figure 2. Based on the final solution, a geometric presentation for the binary system was drawn as displayed in Figure 3.

Table 2 Photometric Solutions for IU Per

Parameter	Best-Fit Value	Formal Error
T_1 (K)	6450*	assumed
T_2 (K)	4790	±15
$q = m_2/m_1$	0.274	±0.002
i (degree)	78.42	±0.03
A_1	1.0*	assumed
A_2	0.50*	assumed
g_1	1.0*	assumed
g_2	0.32*	assumed
X_1	0.658*	assumed
X_2	0.639*	assumed
x_1(V)	0.676*	assumed
x_2(V)	0.804*	assumed
y_1(V)	0.276*	assumed
y_2(V)	0.061*	assumed
Ω_1	2.9845	±0.0051
Ω_2	2.4076	
$r_{1,\rm pole}$	0.3666	±0.0007
$r_{1,\rm point}$	0.3933	±0.0009
$r_{1,\rm side}$	0.3792	±0.0008
$r_{1,\rm back}$	0.3867	±0.0008
$r_{2,\rm pole}$	0.2546	±0.0004
$r_{2,\rm point}$	0.3705	±0.0005
$r_{2,\rm side}$	0.2650	±0.0004
$r_{2,\rm back}$	0.2977	±0.0004
$L_1/(L_1 + L_2)$(V)	0.962	±0.001

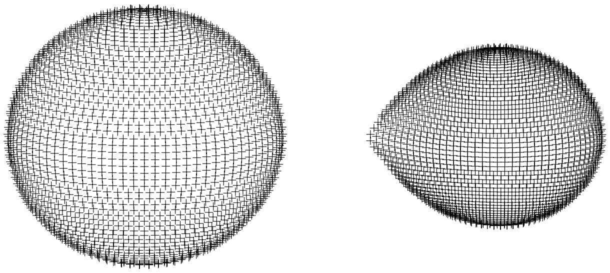

Fig. 3 A geometric configuration of IU Per at phase 0.25.

The photometric solution reveals a semi-detached configuration (mode 5) for the system with the secondary component filling its Roche lobe. It confirms the predictions of Mkrtichian et al. (2004) and Kim et al. (2005) and suggests the very probable mass exchange between the components. The temperature of the secondary is determined to be about 4790 K, implying that it must be a very evolved star. It must be far outside the instability strip in the H-R diagram. This suggests that the intrinsic pulsation of the eclipsing system could not be radiated from the secondary but from the mass-accreting primary component.

4 THE INTRINSIC OSCILLATIONS

For an eclipsing binary with a pulsating (primary) component, the observed light could be approximately interpreted as

$$l_{\rm obs.} = l_1 f_{\rm pul.} + l_2, \tag{3}$$

where l_1 and l_2 are the calculated brightnesses contributed by the primary and secondary components, respectively, and $f_{\rm pul.}$ denotes the pulsating variation of l_1. With the derived photometric solution, we could compute l_1 and l_2 separately at each observation epoch by using the LC code of the Wilson-Devinney package. With this, the 'pure' pulsation light variations from the primary star can then be extracted. The resulting pulsating light curves are shown in Figure 4.

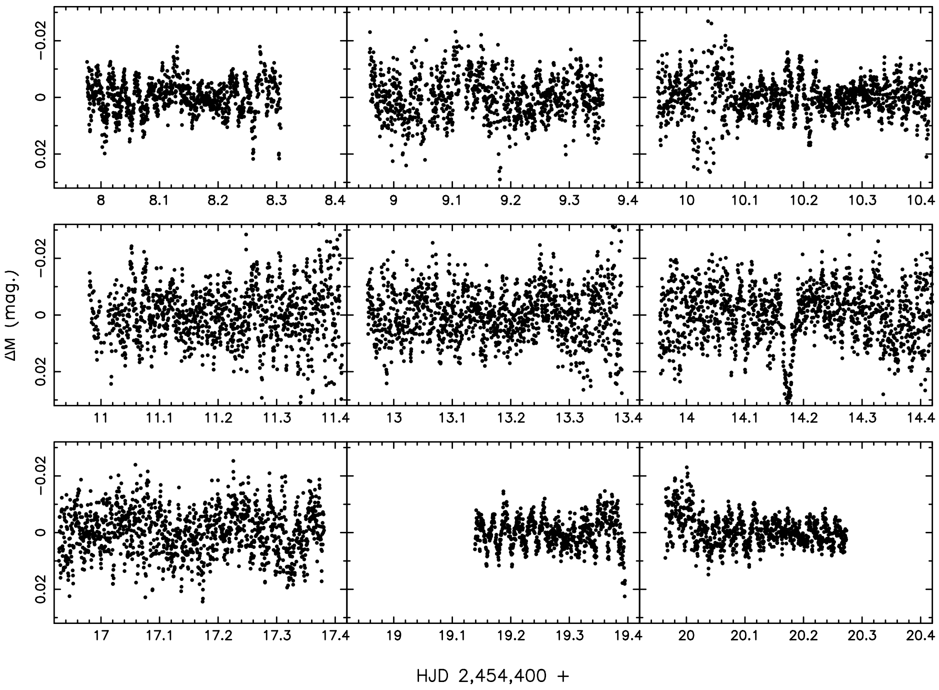

Fig. 4 Pulsation light variations extracted from the CCD photometric data.

A power spectral analysis was then carried out using the algorithm Period04 (Lenz & Breger 2005) so as to investigate the nature of the intrinsic oscillations. In doing that, we selected only those peaks with signal to noise ratios (S/N) larger than 3.0 for further investigation. The noise levels at each frequency were computed using the residuals from the original data when all the trial frequencies were pre-whitened. Considering the probable saturation caused by the orbital modulation, peaks at low frequencies less than 10.0 c/d were excluded from the frequency analysis.

Figure 5 presents the spectral window as well as the step-by-step amplitude spectra conducted from the pulsation data. Each spectral panel in the figure corresponds to the residuals with all the previous frequencies pre-whitened. The main results of the frequency analysis are given in Table 3. In total,

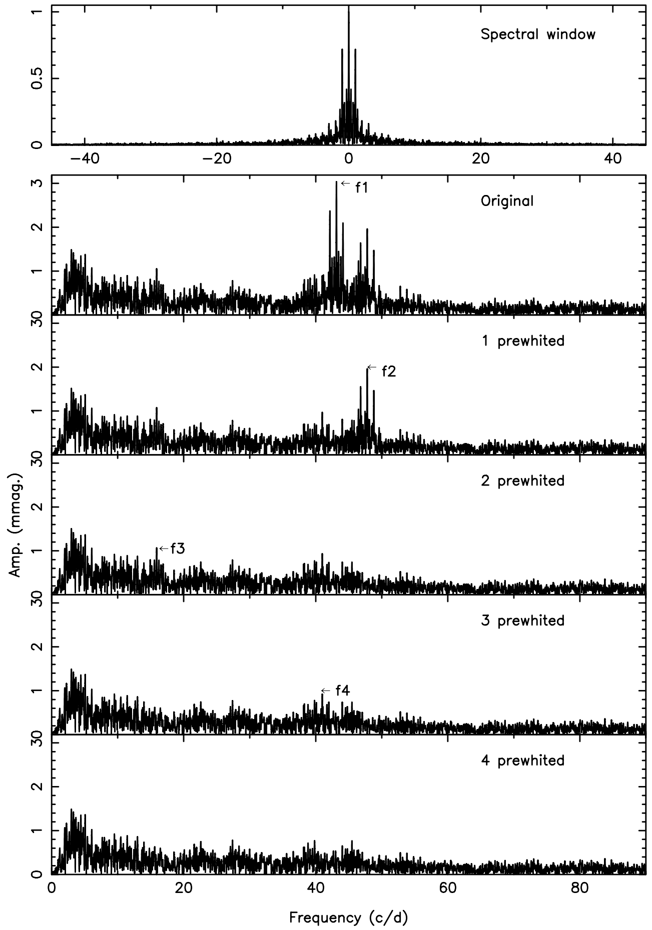

Fig. 5 Spectral window and the amplitude spectra of the intrinsic oscillations of IU Per.

Table 3 Results of the Fourier Analysis

f_i	Frequency (c/d)	Amplitude (mmag)	S/N	Q ($\times$100)	Mode
f_1	43.1314±0.0011	3.08±0.07	11.26	1.194	6H
f_2	47.7959±0.0017	1.94±0.07	8.16		3×F
f_3	15.9031±0.0031	1.06±0.07	3.81	3.239	F
f_4	40.9849±0.0036	0.98±0.07	3.23	1.257	5H

we have detected four peaks with confidence higher than 99.9% from the Fourier analysis. The main amplitude spectrum seems to be dominated by two frequencies at 43.131 c/d and 47.796 c/d. Among the four derived frequencies, f_2 could be interpreted as 3 times that of f_3. The two modes, $f_1' = 42.103$ c/d and $f_2' = 45.806$ c/d, given by Kim et al. (2005) were not detected from the new data. Comparing their results with ours in detail, however, we noted that the two modes from Kim et al. (2005) might be interpreted as the orbital modulated components of f_4 and f_1 in our result, i.e., $f_1' \simeq f_4 + 1/P_{\rm orb}$ and $f_2' \simeq f_1 + 2/P_{\rm orb}$.

The eclipsing light curve synthesis has provided us with some important parameters of the binary system such as the mass ratio and the unified mass radius $r_1 = R_1/A$ (actually, the accurate value of r_1 was obtained by the LC code). With these values, the mean density of the pulsating primary component can be precisely determined. Starting from Kepler's law

$$P_{\rm orb}^2 = \frac{4\pi^2 A^3}{G(M_1 + M_2)}, \tag{4}$$

where $P_{\rm orb}$ is the orbital period of the binary system, M_1 and M_2 are the masses of components, respectively, and $M_1 + M_2 = M_1(1 + q)$. The mean density of the primary star could be deduced as

$$\rho_1/\rho_\odot = \frac{M_1/R_1^3}{M_\odot/R_\odot^3} = \frac{4\pi^2 R_\odot^3}{M_\odot G(1+q) r_1^3 P_{\rm obr}^2}\,. \tag{5}$$

Taking the values of $P_{\rm orb}$, q and r_1 (=0.278±0.01) into Equation (5), the mean density of the pulsating primary star is computed to be $\rho_1/\rho_\odot = 0.265$.

Following the famous formula $Q = P_{\rm pul}(\rho/\rho_\odot)^{1/2}$, the Q value for each of the detected pulsating modes was calculated. Based on which, a mode identification was carried out which compares with Fitch's model (Fitch 1981) as shown in Table 3. It suggests that the mass-accreting primary component is very probably in radial pulsating. The fundamental period could be around 0.0628 d.

5 DISCUSSION AND CONCLUSIONS

Our observations confirm the intrinsic pulsating light variations from the system as reported by Kim et al. (2005). With the first completely covered V-band light curve, we have obtained the first photometric solution for the eclipsing system based on the W-D method. The result reveals a semi-detached configuration for the system with the secondary filling its Roche lobe, which suggests the strong interaction and very probable mass transfer between the components. It also shows that the secondary component could be an evolved K-type star, the rapid pulsating light variations could very likely be from the mass-accreting primary component. Therefore, IU Per could be classified as a certain member of the oscillating EA (oEA) stars, a group of mass-accreting pulsating components in Algol-type semi-detached binaries (Mkrtichian et al. 2004).

From the new observations, we have detected a total of 7 new epoches of light minima. Combining these data with all the photoelectric and CCD observed times of minima collected from available literature, the long-term orbital period change of IU Per was analyzed. The orbital period and the ephemerides of the system were renewed. The result supports the conclusion of Qian (2001) that IU Per must have been undergoing a continuous orbital period decrease during the past decades. For a semi-detached system with a less-massive component filling its Roche-lobe, the orbital period could be generally increasing due to the mass exchange. In the case of IU Per, we conclude that it may be suffering from a significant angular momentum loss, though the mechanism is uncertain.

With the photometric solution, we calculated the light brightness radiating from each component separately at each observation time, and picked the intrinsic pulsating light variations up from the primary star. This seems to be a beneficial attempt at extracting the pulsating light curves from the observational data. A further Fourier analysis detects four confident pulsating modes with S/N larger than 3.0. Also based on the photometric solution, we deduced the mean density of the pulsating component and computed the Q values for each of the derived pulsating modes. A brief mode identification shows that the mass-accreting component of IU Per is very probably in radial pulsation.

In summary, IU Per has been shown to be a very interesting object in many aspects of research. It is a strongly interacting system with mass transfer between the components. It undergoes an unusual change in the orbital period. Moreover, it has proved to be multi-periodic in its pulsation. Further observations, especially radial-velocity spectroscopy, are urgently needed.

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