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PULSATION OF IU PER FROM THE GROUND-BASED AND 'INTEGRAL' PHOTOMETRY

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Abstract. IU Per is an eclipsing semi-detached binary with a pulsating component. Using our own ground-based, as well as INTEGRAL satellite photometric observations in the B and V passbands, we derived geometrical and physical parameters of this system. We detected the short-term variations of IU Per in the residuals of brightness after the subtraction of synthetic light curves. Analysis of these residuals enabled us to characterize and localize the source of short-term variations as the pulsations of the primary component typical to δ Scuti-type stars.

Key words: stars: binaries: eclipsing – stars: oscillations – stars: variables: δ Scuti – stars: individual (IU Per)

1. INTRODUCTION

IU Per is an eclipsing semi-detached binary of spectral class A4 (Samus et al. 2004). The behavior of this binary in the O–C diagram was studied by Qian (2001), Kreiner (2004) and Zhang et al. (2009). Qian (2001) collected 102 visual and photographic and one photoelectric minima of IU Per. Using the least square method, he derived a quadratic ephemeris of IU Per and determined decrease of its orbital period, $dP/dt = -4.11 \times 10^{-7}$ d yr^{-1}. Kreiner (2004) detected no change of orbital period and published the following linear ephemeris

$$Min_{\rm I} = {\rm HJD}\ 2\,452\,500.214 + 0.8570257 \times E. \qquad (1)$$

Zhang et al. (2009) constructed the O–C diagram of IU Per using only photoelectric and CCD data (16 published and 7 new minima) and derived the new linear and quadratic ephemerides:

$$Min_{\rm I} = {\rm HJD}\ 2454413.0933(5) + 0.85702543(20) \times E, \qquad (2)$$

$$Min_{\rm I} = {\rm HJD}\,2454413.0920(7) + 0.85702357(70) \times E - 2.53(92) \times 10^{-10} \times E^2\ . \quad (3)$$

They concluded that the orbital period of this system continuously decreases with the rate $dP/dt = -2.2 \cdot 10^{-7}$ d yr^{-1}.

Budding et al. (2004) published the basic parameters of IU Per: the mass ratio 0.27, the relative radius of the primary component with respect to the separation of stars 0.374 and the inclination 82°. They concluded that this system is probably semi-detached (SD) with the components of spectral classes A4 and G6 IV. These results were used by Kim et al. (2005) as input parameters for their analysis of the photometric observations of IU Per. They derived a model of this system using the Wilson & Devinney (1971) code and showed that the secondary component fills its inner Roche lobe. They analyzed the residuals of observations after subtracting synthetic light curves using multi-frequency analysis by Kim & Lee (1996). The following two frequencies in these residuals were detected: $f_1 = 42.103$ c/d (0.024 d) and $f_2 = 45.806$ c/d (0.022 d). The primary component was classified as a pulsating variable of δ Scuti type with the pulsation period $\sim$ 34 min, the amplitude of pulsations 0.02 mag in the B filter and multi-periodicity. They classified the system as oEA type (oscillating eclipsing Algol, named by Mkrtichian et al. 2004).

Zhang et al. (2009) studied the pulsating activity of the primary component of IU Per and analyzed the residuals of its light curve by the method of Fourier transformation. The results of their analysis suggested that the primary component may be a radial pulsator with a fundamental period of about 0.0628 d.

2. OBSERVATIONS

The observational material was obtained at the Observatories of the Astronomical Institute of the Slovak Academy of Sciences from November 2006 till January 2012. The comparison and control stars were GSC 02858-02003 ($B = 12.24$ mag, $V = 11.88$ mag) and GSC 02859-00794 ($B = 11.85$ mag, $V = 11.36$ mag). Observations in B and V filters were organized to cover all the light curve with high density of data points, with a reasonable signal-to-noise ratio. A detailed description of the photometric equipment, as well as the reduction procedures, was recently published by Hric et al. (2011).

We also used the results of photometric observations obtained with the Optical Monitoring Camera (OMC) onboard the INTEGRAL satellite. OMC is a small refractor (the diameter 50 mm and the focal length 153.7 mm) equipped with a CCD camera with 1024×1024 pixels. The data correspond to the V system. The INTEGRAL satellite is primarily specialized for objects of high energy astrophysics, but the wide field of OMC (5°) is also useful for obtaining light curves of variable stars.

The photometric data of IU Per (189 exposures with sampling time of 1 s) were taken from the public OMC archive[1]. The observations cover the time from 2004 August 1 to 4 (JD 2 453 219.1 − 2 453 221.7) by three exposure times, 10, 30 and 100 s, with the average errors 0.04, 0.02 and 0.01 mag, respectively. Individual exposures were co-added to obtain one photometric point of 10 min duration, with 630 s sampling. Images with the exposures shorter than 20 s were rejected to increase the signal-to-noise ratio of the combined image.

3. ANALYSIS

The light curve of IU Per exhibits, except the mutual eclipsing variability, also the short-term variations, mainly in the phases out of the primary minima. These variations are probably due to pulsations of the primary component. Moreover,

[1] sdc.cab.inta-csic.es/omc/index.jsp

Table 1. The times of minimum light (six primary and one secondary) in B and V filters.

Date	JD (heliocentric)	
	B	V
2006 12 11	2 454 081.4236 ± 0.0002	-
2007 08 07	2 454 320.5389 ± 0.0003	2 454 320.5389 ± 0.0017
2009 09 18	2 455 093.5721 ± 0.0004	2 455 093.5721 ± 0.0005
2011 09 26	2 455 831.4691 ± 0.0008	2 455 831.4690 ± 0.0007
2011 09 27	2 455 832.3256 ± 0.0007	2 455 832.3260 ± 0.0006
2011 11 06	2 455 872.6063 ± 0.0003	2 455 872.6067 ± 0.0003
2012 01 28	2 455 955.3178 ± 0.0023	2 455 955.3136 ± 0.0016

our observations revealed the enhanced variability after the primary minima. The reason of these variations is not fully understood, they can be related to interaction between the components of this semi-detached binary. The aim of our analysis was to identify and explain the reason of short-term variations seen in the light curves.

3.1. Analysis of the O–C diagram

Our CCD observations of IU Per cover six primary and one secondary minima usable to determine the times of minimum light with sufficient precision. The times of minimum light were determined by the code MINIMA[2]. We have used the methods of Kordylewski and Kwee-van Woerden, the fit by Fourier polynomial and the method of "sliding integration". The obtained minima are listed in Table 1. The times of minimum light for particular observational nights, used in the analysis of the O–C diagram, were determined as the weighted averages of minima in the corresponding filters.

In addition to the newly determined times of minimum light, we used all available published data for the analysis of the O–C diagram of IU Per. The times of minima were collected from Eclipsing Binaries Minima Database[3] as well as from papers: Hanžl (1994), Agerer & Hubscher (2002), Zejda et al. (2006), Dvorak (2006), Brát et al. (2007, 2008, 2009), Hubscher et al. (2005, 2006, 2008, 2010), Nelson (2008), Samolyk (2008, 2009, 2010, 2011), Zhang et al. (2009), Liakos & Niarchos (2009), Diethelm (2010, 2012, 2013), Lampens et al. (2010) and Hubscher & Lehmann (2012). In total, we applied 197 times of primary minima and 10 times of secondary minima. We computed the O–C values for these minima according to the ephemeris of Kreiner (2004). The corresponding O–C diagram is shown in Figure 1.

Preliminary inspection of the O–C diagram of IU Per indicated a linear long-term trend in data. In this sense, the results of Qian (2001) and Zhang et al. (2009) are quite striking. Qian (2001) probably did not use older times of minimum light ($E < -13\,000$) and therefore he determined only the quadratic ephemeris. Zhang et al. (2009) used merely photoelectric and CCD times of minima, which cover only the last 20 years of observations. It is obvious that their quadratic ephemeris (3) does not describe the long-term trend in the O–C diagram of IU Per at all (see Figure 1).

[2] http://members.shaw.ca/bob.nelson/software1.htm

[3] http://www.oa.uj.edu.pl/ktt/

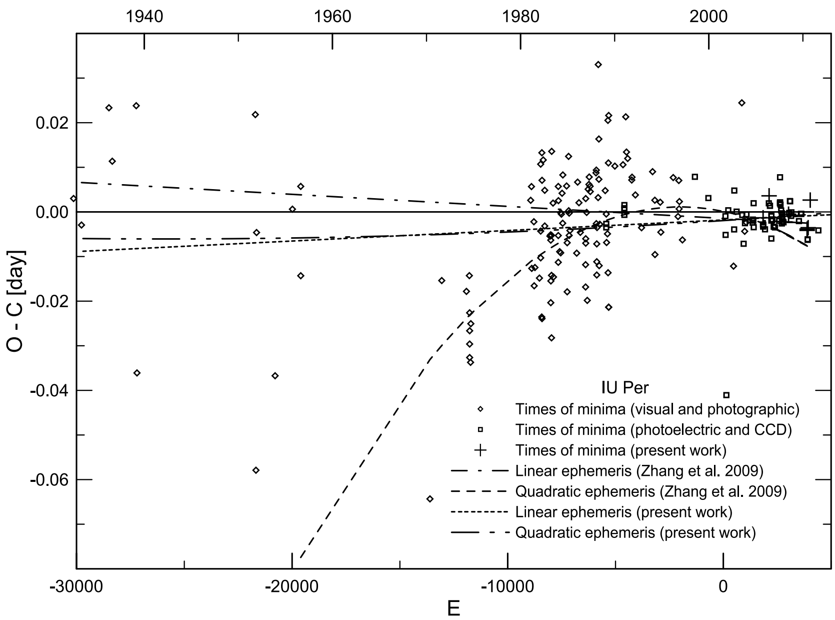

Fig. 1. O–C diagram of IU Per constructed using the linear ephemeris of Kreiner (2004). The epoch is set with respect to our first time of minimum light.

Our dataset consists of 134 visual and photographic, as well as 73 photoelectric and CCD times of minimum light. Whereas the times of minima were obtained using various methods with different accuracy, we set the weights for the particular datasets. Since the errors of the time of minimum light were mostly missing in our sample, the weights were derived by linear fitting of the O–C values for a particular type of detector according the corresponding sum of residual squares. We determined that the weight of photoelectric and CCD observations is 7.5 times higher than the weight of visual and photographic ones.

We fitted the O–C data by weighted least squares method using linear and quadratic polynomials. Resulting ephemerides (see Figure 1) are determined by the equations:

$$Min_{\rm I} = {\rm HJD}\, 2\,455\,093.5727(9) + 0.85702594(1) \times E, \tag{4}$$

$$Min_{\rm I} = {\rm HJD}\, 2\,455\,093.5728(9) + 0.85702602(2) \times E + 6.1(1.3) \times 10^{-12} \times E^2\ . \tag{5}$$

The particular sums of residual squares ($0.0313\,{\rm d}^2$ and $0.0311\,{\rm d}^2$ for the linear and quadratic fits, respectively) are very similar for both fits, therefore it is impossible to unambiguously decide whether inaccurate HJD ($Min_{\rm I}$) and period P values were determined, or the increase of the orbital period plays some role. It is worth to note, that our value of the orbital period of IU Per is very close to the Kreiner (2004) value (1), and the sums of the residual squares for the O–C values, computed according to his linear ephemeris ($0.0338\,{\rm d}^2$), are similar to our values too.

On the other hand, the change of the orbital period in this system is not excluded. Our light curve analysis suggests that the secondary component of IU Per fills its inner Roche lobe (see hereafter), and therefore the mass transfer can take place in this system. The transport of mass from the secondary to the primary component for $q < 1$ results in the increase of the orbital period, which is suggested by our quadratic ephemeris, too. When we assume that the total angular momentum of the binary is preserved, the obtained change of the period $dP/dt = +2.6 \times 10^{-9}$ d yr^{-1} corresponds to an accretion rate of $dM/dt = 9.1 \times 10^{-10}\, M_{\odot}$ yr^{-1}. The problem of the IU Per ephemeris can only be solved using long-term observations of the times of minimum light in future. The linear ephemeris (4) was used for the subsequent analysis of all observational data.

3.2. Modeling of the light curves of IU Per

Our photometric B and V observations cover the light curves of IU Per very well except for small intervals around phase 0.6. However, this gap does not affect the results of the light curve analysis significantly.

In order to determine the physical and geometrical parameters of IU Per, the PHOEBE code (Prša & Zwitter 2005) was used. The limb darkening coefficients of the components (x_1, y_1, x_2, y_2) were determined for the given temperature and gravity by logarithmic interpolation of values in the van Hamme (1993) tables. We updated the values continuously in particular steps of the analysis. The gravity darkening coefficients of the components were set to be $g_1 = 1.0$ and $g_2 = 0.32$ according to Lucy (1967) for the spectral types published by Budding et al. (2004). We took the following bolometric albedos of the components: $A_1 = 1.0$ for a star with the energy transfer by radiation, and $A_2 = 0.5$ for a star with energy transfer by convection (Rucinski 1969). The gravity darkening coefficients and bolometric albedos was fixed during the analysis. We took into account only one reflection of radiation from the surface of the component. The following effective wavelengths of the response curves were used: $\lambda_B = 440$ nm and $\lambda_V = 550$ nm.

The temperature of the primary component, $T_1 = 8450$ K was set according to its spectral class A4 (Budding et al. 2004) and the calibration of Cox (2000), and this value was fixed during the analysis. The input values of the inclination (82°) and the relative size of the primary component (0.374) were adopted from Budding et al. (2004). Since no radial velocities are available for IU Per, and the mass ratio q is the most sensitive parameter for the light curve analysis, we tested its value by a series of preliminary runs of the PHOEBE code with the assumed mass ratios around the value $q = 0.27$ adopted from Budding et al. (2004). The solution with the lowest sum of residual squares was obtained for $q = 0.275$. This value was taken as the initial one for the next analysis. The mass ratio q, potentials of the components Ω_1, Ω_2, the effective temperature of the secondary component T_2 and inclination i were adjusted freely during the light curve analysis.

The final solution yields the following results: the IU Per is a semi-detached system and the secondary component fills its inner Roche lobe. The synthetic light curves constructed by using the obtained physical and geometrical parameters of IU Per are shown in Figure 2. Synthetic light curves in the B and V passbands fitted the observed data very well, except a small deviation around the primary minimum in B. This offset should be related to a higher noise content of the data in this part of the light curve caused by a lower sensibility of the CCD detector in B.

For estimation of the evolutionary status of the components, we have to find their physical parameters. Since the spectroscopic mass ratio is not known, an assumption on the mass of the primary component is to be made. According to

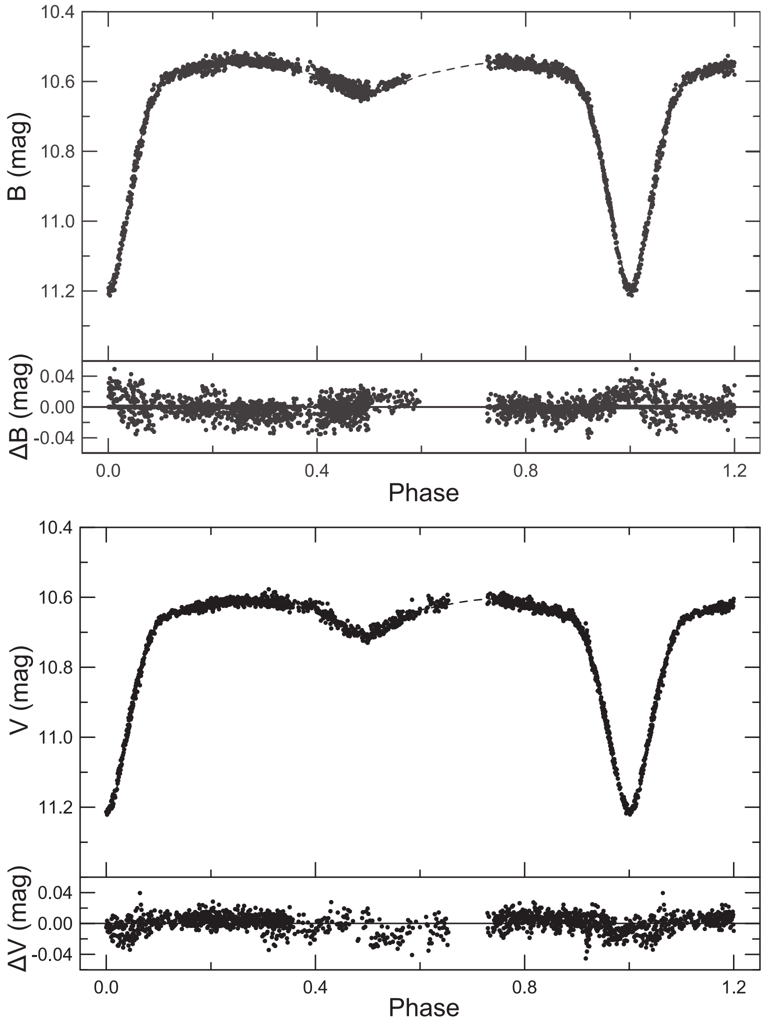

Fig. 2. Synthetic light curves (dashed line) of IU Per in B and V filters. The line is hidden between the observed points, but the fit quality is seen in the bottom plots of residuals.

Cox (2000), the mass of a main-sequence star of spectral type A4 is 2.20 $M_{\odot}$. Other physical and geometrical parameters of this binary were derived using the third Kepler law and the Stefan-Boltzmann law, and are listed in Table 2. From the absolute luminosities we calculated the absolute bolometric magnitudes $M^1_{\rm bol} = 1.54$ mag and $M^2_{\rm bol} = 4.63$ mag for the primary and the secondary components, respectively. From the temperatures we determined bolometric corrections: –0.16 mag for the primary and –0.39 mag for the secondary component. Adopting these values of bolometric corrections, we calculated the absolute visual magnitudes of the components: $M^1_V = 1.70$ mag, $M^2_V = 5.02$ mag. During the secondary eclipse, only the primary component is visible and its apparent visual magnitude is $V_1 = 10.71$ mag. Taking into account interstellar extinction $A_V = 0.62$ (according to maps of galactic dust reddening and extinction[4], the resulting distance of IU Per is 476 pc.

Table 2. Geometrical and physical parameters of IU Per. The effective relative radii were determined on the basis of relative volumes of the components.

Parameter	Primary component	Secondary component
Inclination [°]	78.8 ± 0.4	
Mass ratio	0.273 ± 0.005	
Ω potential	2.41 ± 0.25	2.23 ± 0.29
Effective relative radius	0.38 ± 0.01	0.27 ± 0.02
Effective temp. [K]	8 450*	4 900 ± 250
Mass [$M_\odot$]	2.20*	0.60
Radius [$R_\odot$]	2.04	1.46
Luminosity [$L_\odot$]	19.05	1.10
Separation [$R_\odot$]	5.35	
Limb dark. coef. $X(bol.)$	0.661*	0.641*
Limb dark. coef. $Y(bol.)$	0.154*	0.162*
Limb dark. coef. $x(B)$	0.787*	0.789*
Limb dark. coef. $y(B)$	0.315*	0.301*
Limb dark. coef. $x(V)$	0.682*	0.679*
Limb dark. coef. $y(V)$	0.285*	0.278*

* - assumed

3.3. Period analysis of the light curve residuals

Next we analyzed the residuals of the observations after subtraction of the synthetic light curves. For the period analysis of the residuals we used the method of the discrete Fourier transformation (DFT, Deeming 1975). Inspection of the light curves showed that the short-term brightness variations have vanished during the primary eclipses. Therefore the light curve sections around the primary minima were not analyzed by DFT method. The example of the period analysis of the short-term variation of IU Per observed on 2007 November 5 in V filter is shown in Figure 3. Significant periods were found around values 0.013, 0.017, 0.021 and 0.025 d, while small shifts of the periods were detected from night to night. These shifts may be a demonstration of interaction between the components of the system. The periods 0.021 and 0.025 d are close to those published by Kim et al. (2005) and Zhang et al. (2009).

The vanishing of the periodic short-term variations during primary minima suggests that the primary component is responsible for this variability. Moreover, according the obtained absolute parameters (Table 2), the primary component is a post-MS star lying in the δ Scuti section of the instability strip (see Figure 4). The detected periods are typical for δ Scuti pulsating variables.

The analysis of the light curve has provided us with the parameters which can be used to determine the mean density of the primary component precisely. Specifically, the mass ratio q and the relative radius of the primary $r_1 = R_1/a$, where R_1 is the absolute radius of the primary component and a is the length of the major axis of the binary orbit. If we assume that $M_1 + M_2 = M_1(1+q)$, using

[4] http://irsa.ipac.caltech.edu/applications/DUST/

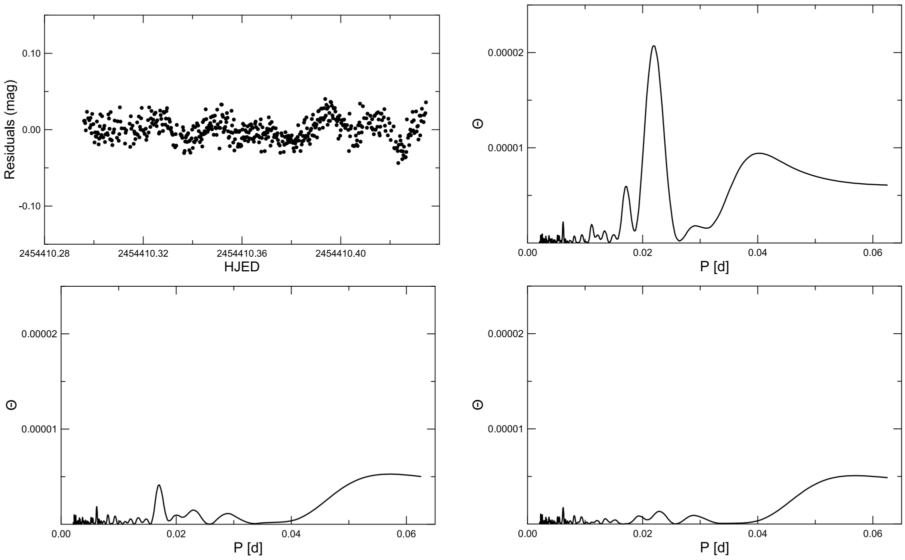

Fig. 3. The example of the period analysis of short-term variations of IU Per observed on 2007 November 5 in the V filter (upper left panel). Power spectrum (upper right panel) obtained by the DFT method shows the most significant periods, 0.021 and 0.017 d. The power spectra after removal of the periods 0.021 and 0.017 d are shown in the bottom panels, left and right respectively.

the third Kepler law we can derive the mean density of the primary component:

$$\rho_1/\rho_\odot = \frac{M_1/R_1^3}{M_\odot/R_\odot^3} = \frac{4\pi R_\odot^3}{G(1+q)r_1^3 P_{\rm orb}^2 M_\odot} \tag{6}$$

where $P_{\rm orb}$ is the orbital period of the binary system. Taking the values of $P_{\rm orb}$, q and $r_1 = 0.38$ (computed using the value of relative volume of the primary) Equation (6) gives $\rho_1/\rho_\odot = 0.26$ Following the formula $Q = P_{\rm pul}(\rho/\rho_\odot)^{1/2}$, we calculated the pulsation constants Q for the periods of pulsations 0.013, 0.017, 0.021 and 0.025 d detected by the DFT method. The obtained values of the pulsation constant are 0.0064, 0.0085, 0.0106 and 0.0128.

On the basis of published pulsation models of the δ Scuti stars (Fitch 1981) we identified the following modes of pulsations: the fifth harmonic radial mode $5H$ and the seventh harmonic non-radial mode p_7 for the pulsation constants 0.0106 and 0.0128, respectively. The pulsation constants 0.0064 and 0.0085 probably represent the higher harmonics of the radial and non-radial pulsations. The position of the primary component of IU Per in the HR diagram (Figure 4) also suggests the pulsation of this star in a higher harmonic mode. We can conclude, that the primary component of IU Per is a pulsating variable of δ Scuti type with radial and non-radial pulsations.

3.4. Photometric data from the INTEGRAL

The INTEGRAL/OMC observational data of IU Per with the corresponding errors are plotted in Figure 5 (left panel). The distribution of magnitudes does not allow us to determine the times of minimum light, but the phase diagram

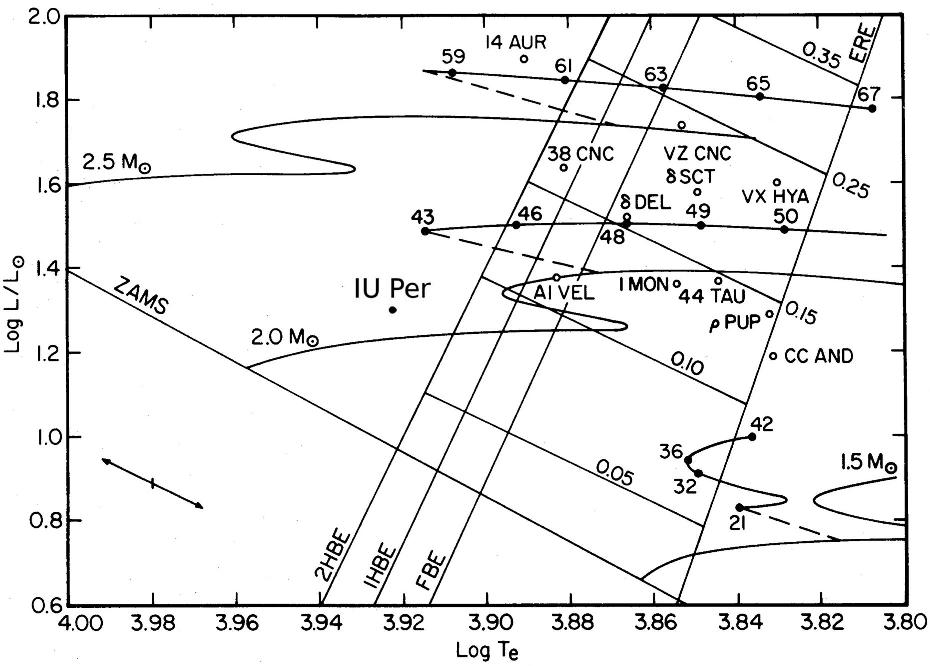

Fig. 4. The position of the primary component of IU Per (full circle) together with other variable stars of δ Scuti type in the HR diagram taken from Fitch (1981). Line ERE represents the belt limits of cepheid non-stability. The lines of the basic modes of pulsations for the periods 0.05, 0.10, 0.15, 0.25 and 0.35 days are almost parallel to the ZAMS line. The lines 2HBE, 1HBE and FBE show the borders of instability for the basic (F), first (1H) and second (2H) harmonic modes of pulsations, for the stars with the metallicity $Z = 0.02$. The arrows in the left bottom corner show the variations of the star position when its temperature changes by 1200 K.

of the light curve constructed using the obtained linear ephemeris (right panel of Figure 5) confirms the relevancy of our O–C analysis. The synthetic light curve in V determined on the basis of our physical and geometrical parameters of IU Per is also presented in both panels of Figure 5. The synthetic light curve fits the observed data well, and this supports the results of our light curve modeling.

The residuals of the INTEGRAL/OMC observations after subtracting the synthetic light curve (bottom parts of diagrams plotted in Figure 5), suggest the presence of the intrinsic short-term variability caused by pulsation activity of the primary component of IU Per. These residuals were used for a period analysis except the data obtained during the primary minima as well as the observations around JD 2 453 219.2, which show peculiar behavior. The period analysis provided us the significant periods around 1.80 and 1.46 h. These periods probably are unreal, and they only reflect the distribution of OMC observations. It is worth to note, that Zhang et al. (2009) mentioned a period of 0.0628 d as the fundamental period of radial pulsations of the primary component of IU Per.

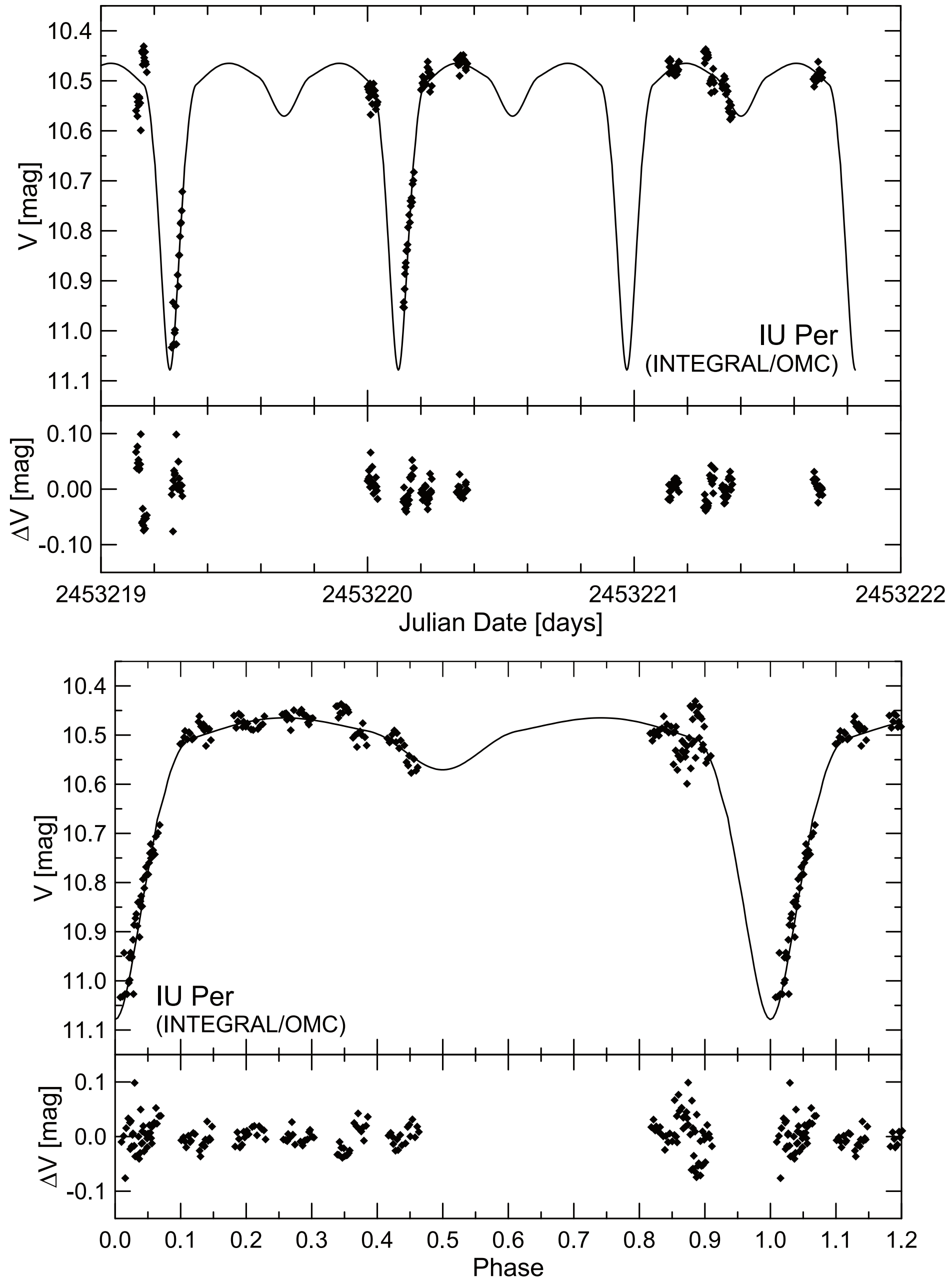

Fig. 5. The INTEGRAL/OMC observations of IU Per plotted together with the synthetic light curve in the filter V. The residuals are also plotted below the light curve (upper panel) as well as in the phase diagram (bottom panel).

4. CONCLUSIONS

Analyzing the light curve of eclipsing binary IU Per in B and V passbands, we derived the physical and geometrical parameters of both components (Table 2) and constructed a model of this semi-detached system. Our analysis of the residuals confirms the presence of intrinsic short-term variability in light curves of IU Per. Owing to the disappearance of these variations close to the primary minima, we deduced that their source is related to the primary component. The period analysis revealed the presence of multiple periodic variations in the residuals with the periods 0.013, 0.017, 0.021 and 0.025 d, while their values were slightly shifted on particular nights.

Our study of the evolutionary status of the primary component of IU Per confirms, that in the HR diagram this star is located in the area of pulsating stars of δ Scuti type (Figure 4). The detected periodic short-term variations probably originate in pulsations of the primary component of IU Per. The position of this star in the HR diagram, as well as our period analysis of residuals, suggest that the primary component of IU Per pulsates not in the basic mode, but in higher harmonic modes where one mode of pulsations is radial and the second one is non-radial.

Our light curve analysis confirmed, that the secondary component of IU Per fills its inner Roche lobe. This configuration should lead to the mass transfer between the components and the subsequent increase of the orbital period of this binary system. Our analysis of the O–C diagram also supports such a model. The matter transferred onto the surface of the primary component can lead to the observed changes of its pulsation periods.

On the basis of analysis of the present set of the times of minimal light, it is impossible to decide if there is a change of the orbital period of IU Per. Additional long-term observations are necessary to unambiguously solve this open question. Further photometric observations with a better signal-to-noise ratio would be also important for a better understanding the observed changes of pulsation periods of the primary component of IU Per.

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