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The long-period RS Canum Venaticorum binary IM Pegasi

I. Orbital and stellar parameters*

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Abstract. New high-resolution and high signal-to-noise ratio spectroscopic observations carried out in 1996–1997 are analysed. A total of 85 new high quality radial velocity measurements are used for determining the new orbital parameters: T_{conj}=HJD2450342.883+24.64880E, e=0.0, γ=–14.09 km s^{-1}, K_1=34.39 km s^{-1}. A model atmosphere analysis of the averaged spectrum of the star has yielded a self-consistent set of fundamental parameters of the primary component: T_{eff}=4450 K, log g=2.4, [M/H]=0.0, ξ_t=1.6 km s^{-1}, v sin$i$=26.5 km s^{-1}. The primary is found to be a typical K2 III giant with the mass of about 1.5 $M_\odot$ which has undergone the first convective mixing on the Red Giant Branch ([C/H]=–0.32, [N/H]=0.30, C/N=1.15). The unspotted V magnitude of the star of $5\overset{m}{.}55$ is estimated from the observed variations of the TiO band and quasi-simultaneous photometry. Combining all parameters, the radius and inclination of the primary as well as a probable spectral class of the secondary are estimated.

Key words: stars: abundances – stars: activity – stars: binaries: spectroscopic – stars: fundamental parameters – stars: individual: IM Peg – stars: late-type

1. Introduction

IM Pegasi (HD 216489) is a long-period ($24\overset{d}{.}6$) single-line spectroscopic binary classified as an RS CVn type star by Hall (1976). It appears to have a circular orbit and almost synchronized rotation. The spotted K2 II-III primary shows significant light curve variations with the maximum amplitude in the V band of $0\overset{m}{.}3$ (Strassmeier et al. 1997). IM Peg also shows rotational modulation of the Ca II infrared triplet, Hα, and Mg II h&k emission (Huenemoerder et al. 1990, Dempsey et al. 1993, 1996). From a single spectropolarimetric measurement, the magnetic field was clearly detected on the star by Donati et al. (1997).

The present paper is the first part of our study of the star. Here, we present our observations from 1996 and 1997 and determine new orbital elements and stellar parameters with better accuracy than those previously obtained. These new parameters are used in our subsequent papers where we study the spot distribution on the stellar surface with the surface imaging technique and chromospheric activity of the star.

2. Observations and data reduction

In 1996 spectroscopic observations were carried out with the coudé spectrograph on the 2.6 m telescope of the Crimean Astrophysical Observatory. The spectra were obtained with the 1st camera equipped with a CCD detector SDS 9000, Photometrics GmbH of 1024×400 pixels. With the slit of $0\overset{''}{.}4$ and dispersion of 65 mÅ/pix a resolving power of about 40 000 was achieved. The covered spectral range was about 60 Å centered at 6170 Å. Two exposures of ≈20 min were typically obtained, that provided the signal-to-noise ratio of an individual exposure of about 250.

In 1997 the star was observed with the SOFIN échelle spectrograph fed by the 2.56 m Nordic Optical Telescope (NOT), La Palma, Canarias. The data were acquired with the 2nd camera equipped with a CCD detector of 1152×298 pixels. Two échelle frames centered at 6180 Å and 7055 Å almost completely covered the spectral range of approximately 5500–8500 Å. For all observing runs the projected width of the slit was set to be $0\overset{''}{.}5$ on the sky, providing a spectral resolving power $\lambda/\Delta\lambda$ ≈ 83 000. With this setup, the dispersion at 6170 Å was 37 mÅ/pix. A typical exposure time of 15 min achieved a signal-to-noise ratio of about 200 for most spectra.

The reduction of the SOFIN data, described by Ilyin (1997), included bias, scattered light, and flat-field corrections, extraction of spectral orders, and wavelength calibration. The latter is obtained with a thorium-argon comparison spectrum. Finally, the wavelengths were corrected for the Earth's motion. The Crimean spectra were reduced similarly except for the steps specifically relating to the échelle spectra. The Julian dates of all spectroscopic observations are given in Table 1.

3. Parameters of the orbit

A total of 85 new observations were used to determine new orbital parameters. The radial velocities were measured by cross-

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* based on observations collected at the 2.6 m telescope of the Crimean Astrophysical Observatory, Ukraine and the Nordic Optical Telescope (NOT), La Palma, Spain

Table 1. Radial velocities data

HJD 2450000+	RV, $\mathrm{km\,s^{-1}}$	ref	HJD 2450000+	RV, $\mathrm{km\,s^{-1}}$	ref	HJD 2450000+	RV, $\mathrm{km\,s^{-1}}$	ref	HJD 2450000+	RV, $\mathrm{km\,s^{-1}}$	ref
320.3855	–29.820	1	409.1188	16.604	1	624.6155	–28.805	2	683.7237	16.456	2
324.4004	–49.804	1	410.2835	19.110	1	624.6230	–28.651	2	683.7322	16.635	2
325.4121	–50.194	1	412.1521	16.648	1	625.6353	–20.295	2	735.5340	1.061	2
326.3850	–46.690	1	413.1524	15.327	1	625.6435	–20.273	2	735.5446	0.963	2
327.4263	–42.358	1	414.1480	6.116	1	626.6567	–11.539	2	736.5674	–8.222	2
331.3644	–8.045	1	415.1713	2.093	1	626.6624	–11.330	2	737.3925	–15.473	2
348.2273	–49.210	1	417.1289	–16.450	1	627.6452	–2.943	2	794.2832	–45.070	2
353.2663	–33.140	1	418.1573	–21.981	1	627.6518	–2.845	2	795.3332	–40.677	2
357.3160	0.928	1	420.1373	–39.040	1	676.6828	–5.390	2	795.3449	–40.762	2
359.2699	14.473	1	421.1315	–44.218	1	676.6902	–5.308	2	796.3377	–34.745	2
360.2654	17.094	1				677.7337	3.437	2	797.3047	–27.500	2
364.3888	10.661	1	617.7301	–42.261	2	677.7404	3.533	2	797.3911	–26.930	2
365.4010	1.563	1	618.6913	–45.753	2	678.7014	10.141	2	797.4123	–26.954	2
376.2793	–43.734	1	618.7026	–45.926	2	678.7074	10.209	2	802.3858	12.943	2
401.1248	–41.540	1	619.7147	–48.013	2	679.7178	15.642	2	804.3108	19.978	2
402.1285	–37.521	1	620.6375	–48.207	2	679.7239	15.556	2	804.3199	19.818	2
403.1255	–27.474	1	620.6452	–48.145	2	680.7042	19.285	2	805.3023	20.061	2
404.1280	–18.953	1	621.7066	–46.026	2	680.7103	19.239	2	805.3078	20.083	2
405.1257	–9.814	1	621.7164	–45.820	2	681.6908	20.580	2	806.3119	18.387	2
406.1570	–4.296	1	622.6684	–41.673	2	681.6968	20.506	2	806.3244	18.527	2
407.1349	7.009	1	623.6625	–35.783	2	682.6949	19.589	2			
408.2645	11.931	1	623.6702	–35.710	2	682.7010	19.666	2			

References (ref): 1 – Crimean observations, 2 – SOFIN observations.

correlating the observed spectra with the synthetic spectra calculated with appropriate atmospheric parameters. Such a procedure was successfully applied to e.g. II Peg observations by Berdyugina et al. (1998), where the zero-point velocity of the SOFIN spectrograph of about 0.3 $\mathrm{km\,s^{-1}}$ for the end of 1996 was estimated. From the SOFIN data we used spectra of seven orders which were free from the Earth atmosphere absorption. No systematic velocity trend among orders was found. The accuracy of the RV measurements averaged from the orders was about 0.15 $\mathrm{km\,s^{-1}}$, while for the Crimean observations it was about 0.8 $\mathrm{km\,s^{-1}}$. The measurements are presented in Table 1. Earlier radial velocity measurements of IM Peg, 20 RVs from Harper (1920, 1935) and 19 RVs from Oláh et al. (1998), were used in the period determination. So, the available data presently consist of 125 values spanning from 1919 to 1997.

For our purpose we used the program FOTEL3 developed by Hadrava (1995), which is able to deduce the orbital period value together with other parameters for both circular and eccentric orbits. The first step was to determine new values of the period P and eccentricity e. A first solution was found for all radial velocity measurements with equal weights. The fit allowed different γ-velocities for different data sets: γ(Harper)=–13.14±0.38 $\mathrm{km\,s^{-1}}$, γ(Oláh et al.)= –13.31±0.37 $\mathrm{km\,s^{-1}}$, γ(Crimea)=–14.88±0.20 $\mathrm{km\,s^{-1}}$, γ(SOFIN)=–14.09±0.04 $\mathrm{km\,s^{-1}}$. The period and eccentricity values were found to be $24\overset{d}{.}64880\pm0\overset{d}{.}00005$ and 0.006±0.007, respectively. In comparison to the recently published values of P and e by Oláh et al. (1998), the new value of the period is more accurate, and that of the eccentricity is one order less. Such a small value of the eccentricity can be ignored for the present, and the orbit can be considered as circular.

Table 2. Orbital elements

Element	Value
P, days	24.64880±0.00005
e	0.006±0.007
K_1, $\mathrm{km\,s^{-1}}$	34.42±0.06
$a_1 \sin i$, $R_\odot$	16.76±0.04
f_1(m), $M_\odot$	0.1042±0.0006
$T_{\rm conj}$, HJD	2450342.883±0.007
γ, $\mathrm{km\,s^{-1}}$	–14.09±0.04

The accuracy of the data sets is rather different and the new SOFIN measurements are significantly more accurate. For this reason, we assumed the period from the all-data solution and the eccentricity to be zero and found the best solution from the SOFIN data only. The solution is given in Table 2, and the measurements phased with the ephemeris

$$T_{\rm conj} = 2450342.883 + 24.64880E \quad (1)$$

are shown in Fig. 1. The epoch corresponds to the conjunction with the primary in the back. This ephemeris is used throughout this paper for all observations.

4. Stellar parameters

4.1. $T_{\rm eff}$, log g, and metallicity

For determining atmospheric parameters of the primary, the 53 SOFIN spectra were averaged, and the resulting spectrum with

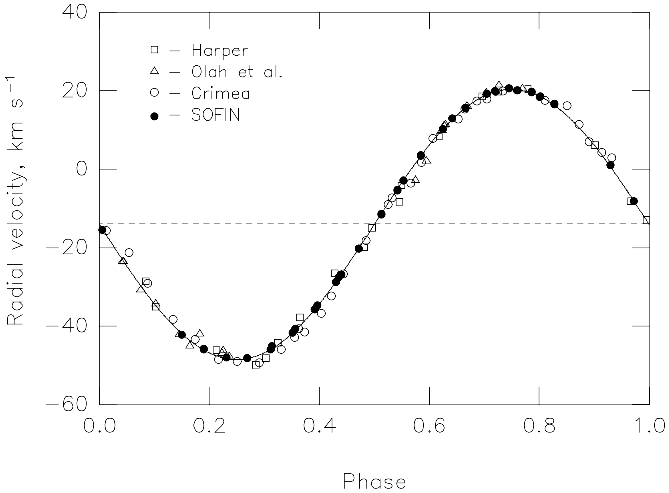

Fig. 1. Radial velocity measurements phased with the new ephemeris $T_{conj} = 2450342.883 + 24.64880\,E$. The solution from Table 2 is shown as a solid line. The γ-velocities of the sets are reduced to the SOFIN value.

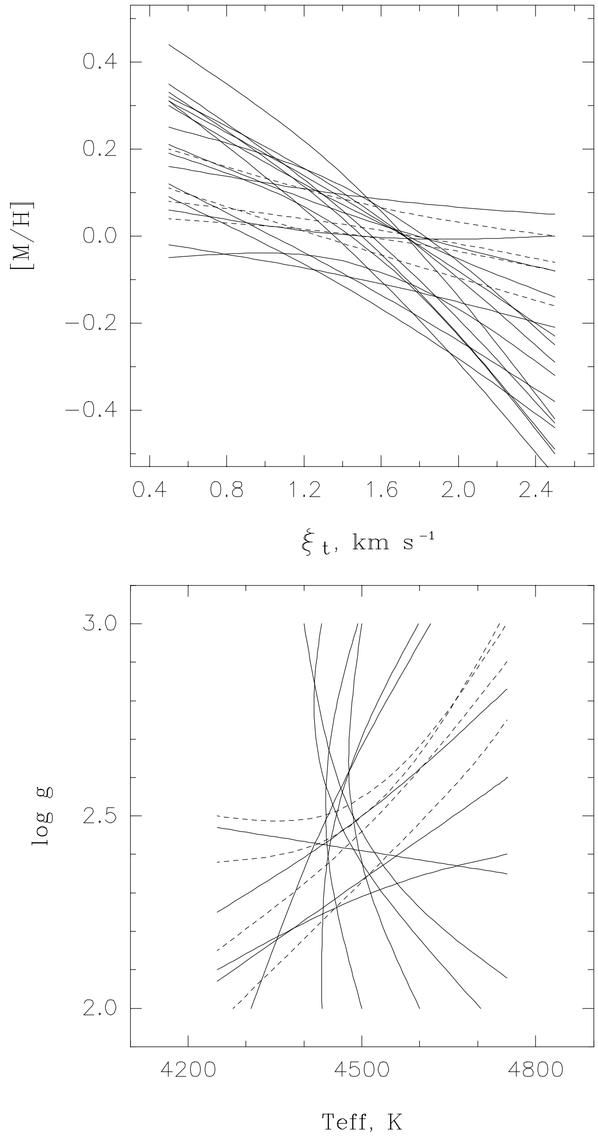

Fig. 2. Diagrams for the self-consistent determination of the atmospheric parameters of the primary of IM Peg: metallicity [M/H], microturbulence ξ_t (*upper panel*) and effective temperature T_{eff}, surface gravity $\log g$ (*low panel*). Curves present loci of the best fitted spectral lines with the synthetic spectrum: Fe I, Si I and Ca I (solid curves) and Fe II and Si II (dashed curves). The curves intersect in narrow regions which provide estimates of the parameters. These are presented in Table 3.

S/N≈1000 covering almost all the region from 5500 Å to 8500 Å was used in the analysis. The spot contribution to the averaged spectrum was found to be insignificant. The effective temperature T_{eff}, surface gravity $\log g$, metallicity [M/H], and microturbulence ξ_t are determined as a self-consistent set of parameters using the synthetic spectra calculations.

A list of atomic line parameters for a given wavelength region was obtained from VALD (Piskunov et al. 1995). It was checked by comparison of the calculated spectrum with the observed one of a slow rotating normal giant β Gem (K0 IIIb), as was done in our recent analysis of the other active star II Peg (Berdyugina et al. 1998). A great number of molecular lines have been added to the list, since their presence in spectra of cool giants is quite noticeable. Stellar model atmospheres used are from Kurucz (1993). A code used for the synthetic spectrum calculations is described in detail by Berdyugina (1991).

Estimates of the projected rotational velocity obtained by different authors are somewhat scattered: 24 km s^{-1}(Ottmann et al. 1998), 25±1 km s^{-1}(Donati et al. 1997), 25.6±1 km s^{-1}(De Medeiros & Mayor 1995), 28.2±1 km s^{-1}(Fekel 1997). Possessing the excellent quality observed spectrum, we have obtained our own estimates of the rotational velocity, $v\sin i$, and macroturbulence, ζ_t. A number of strong and well isolated lines were studied with the Fourier transform. The following values were determined: $v\sin i$=26.5±0.5 km s^{-1} and ζ_t=4.0±0.5 km s^{-1}.

To determine the atmospheric parameters, a total of about 20 lines of Fe I, Fe II, Si I, Si II, and Ca I were chosen. Assuming first an appropriate pair of T_{eff} and $\log g$, we produced a set of curves (loci of the best fitted lines) on a diagram of metal abundance, [M/H], as a function of microturbulence ξ_t (Fig. 2). The curves intersected in a narrow region which provided an initial estimate for a pair of [M/H] and ξ_t. With these values, a set of loci on a diagram of T_{eff} versus $\log g$ was calculated. Their intersection gave an initial estimate of a pair of T_{eff} and $\log g$ values. After a few iterations a self-consistent set of the parameters was found. These are presented in Table 3.

With the atmospheric parameters obtained, the primary of IM Peg is classified as K2 III, in reasonable agreement with the previous classification. It has solar metallicity with an uncertainty of ±0.1 (assuming for the Sun Fe/H=7.55, Si/H=7.50, Ca/H=6.32). The spectrum of the star was recently analysed by Ottmann et al. (1998). As a temperature indicator they used the Hα line which is significantly disturbed by the variable emission, as seen in our spectra. This resulted in remarkable over-

Table 3. Atmospheric parameters of the primary of IM Peg

Parameter	Value
$T_{\rm eff}$, K	4450±50
$\log g$	2.4±0.1
[M/H]	0.0±0.1
$\xi_{\rm t}$, km s^{-1}	1.6±0.2
$\zeta_{\rm t}$, km s^{-1}	4.0±0.5
$v \sin i$, km s^{-1}	26.5±0.5

estimation of the effective temperature and, as a consequence, the surface gravity.

4.2. The CNO abundances

The abundances of the CNO-elements are good indicators of the stellar evolution. In the spectrum of IM Peg many appropriate features can be found for determining the carbon and nitrogen abundances: rotational transitions in vibrational bands of the CN ($A^2\Pi - X^2\Sigma$) red system and C_2 ($A^3\Pi_g - X^3\Pi_u$) Swan system. For the oxygen abundance, no good features can be found: high-excitation lines of O I are obviously disturbed by the active chromosphere, and the line of [O I] at 6363 Å is blended too much. Therefore, it is reasonable to assume that the oxygen abundance in IM Peg is of the solar value (O/H=8.92, Lambert 1978) and we can then determine the abundances of C and N.

For the synthetic spectra calculations we used the line lists provided by Davis & Phillips (1963) and Phillips & Davis (1968). The band oscillator strengths and molecular constants were obtained from the RADEN database (Kuznetsova et al. 1993). Lower level excitation energies and rotational intensity factors were calculated with formulae from the book by Kovacs (1969). The number densities of CN and C_2 were calculated under the assumption of their dissociative equilibrium with a great number of atoms and molecules. The procedure used for determining the CNO abundances is similar to that described by Berdyugina (1993).

The carbon abundance, [C/H]=–0.32, was determined from the head of the C_2 (0,1) band at 5633 Å. The feature is blended partly by atomic lines, but the accuracy of about 0.1 for the abundance can be easily achieved. The nitrogen abundance, [N/H]=0.30, was determined from the heads of the CN (2,0) and (3,1) bands and numerous features from those bands in the regions 7895–7900 Å and 8039–8065 Å. The internal accuracy of the nitrogen abundance is about 0.05. The resulting C/N ratio of 1.15 corresponds well to an evolved giant which has undergone the first convective mixing in its atmosphere on the Red Giant Branch.

4.3. Fundamental parameters of the components

The value of the unspotted V magnitude of the star is important for estimating the fundamental parameters of the binary components. It can be determined from the variability of the TiO bands. The effective temperature of the primary is too high to show evidence of the TiO bands in the spectrum from the unspotted photosphere. Nevertheless, a noticeable depression due to TiO lines is seen at λ7054 Å, at the head of the strong band γ(0,0)R_3, that is typical for spotted G-K stars. The depth of the band correlates well with the V magnitude, in other words, with the spot visibility (Fig. 3). The quasi-simultaneous photometric observations used will be presented in our forthcoming paper. We suggest that the zero value of the central depth corresponds to the unspotted magnitude of the star, V_0. Then, from the linear regression fitted to the data we estimate V_0=5$^{\rm m}_{.}$55±0$^{\rm m}_{.}$05. It is close to the brightest maximum of V=5$^{\rm m}_{.}$6 ever observed (Strassmeier et al. 1997). The value of V_0 should be corrected for the interstellar extinction, but the latter is expected to be of the same order as the uncertainty of V_0. Thus, with the parallax value of 0$''_{.}$01033 from the Hipparcos Catalogue, an absolute magnitude M_V=0$^{\rm m}_{.}$62 can be found. It is very close to the statistical value of 0$^{\rm m}_{.}$5 for K2 III stars (Lang 1992). This is in good agreement with the newly determined atmospheric parameters of the primary.

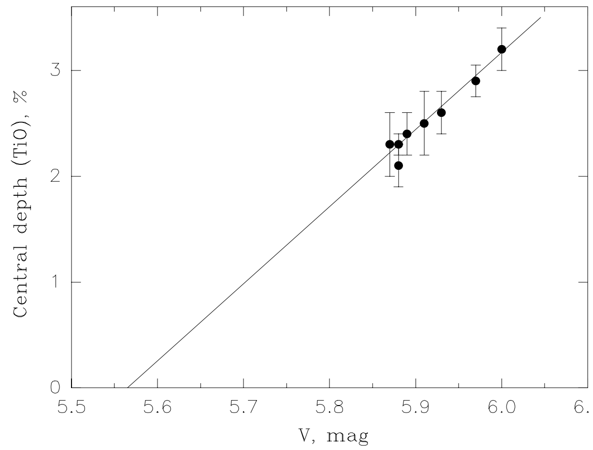

Fig. 3. The variation of the central depth of the TiO γ(0,0)R_3 band at 7054 Å with the V magnitude (dots with error bars). The line represents a linear regression fitted to the data and indicates the unspotted V magnitude of IM Peg when the depth of the TiO band is equal to zero.

The projected rotational velocity of 26.5 km s^{-1} and the photometric period of the star of 24$^{\rm d}_{.}$39 (Strassmeier et al. 1993) result in the relation $R_1 \geq 12.7\,R_\odot$. This corresponds to the radius of a giant with a spectral class of K0–K2 III. From the mass function f_1(m) a mass-mass diagram for various combinations of masses and orbital inclination can be calculated (Fig. 4). Under the assumption that the stellar rotational axis is perpendicular to the orbital plane, one can estimate the masses of the binary components, the primary's radius and the inclination. Such an assumption is justified for synchronously rotating RS CVn binaries (Glebocki & Stawikowski 1995). The low limit of R_1 and the value of $\log g$=2.4±0.1 determine the probable range for the masses of the binary components. This range can be restricted from above by the upper limit of the secondary's mass. Since with present observing techniques the secondary is invisible at all wavelengths, its luminosity should be at least 100 times less than that of the primary, i.e. $M_V \leq 5^{\rm m}_{.}6$. This corresponds to a G8 main sequence

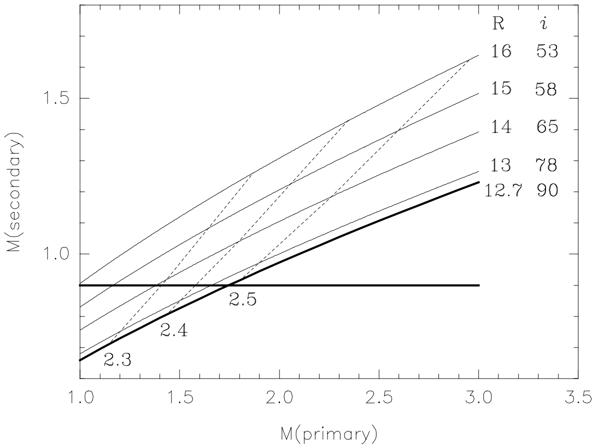

Fig. 4. The mass-mass diagram for IM Peg (in solar units). The thin solid curves are calculated for the fixed values of the radius of the primary and the inclination (numbers in the left). The dashed lines are loci of the primary with a fixed value of log *g* (numbers at the bottom). The probable parameters of the binary components are in the area restricted by the heavy solid lines with $R_1 > 12.7\ R_\odot$ and $M_2 < 0.9\ M_\odot$ and next to log *g*=2.4

star with a mass of 0.9 $M_\odot$ (Lang 1992). Then, in the mass-mass diagram the probable range for all parameters is significantly reduced. With log *g*=2.4±0.1 one can find the following values: $M_1/M_\odot$=1.5±0.2, $R_1/R_\odot$=13.3±0.6, 65°≤ i ≤80°, $M_2/M_\odot$=0.8±0.1. Note that the secondary's mass cannot be less than 0.7 $M_\odot$ because of the low limit of log *g*. Therefore, it could be e.g. a K0 dwarf.

5. Summary

From new high-resolution and high S/N spectra of IM Peg, the following results have been obtained:

1. New orbital parameters have been determined, the ephemeris being improved: $T_{\rm conj}$ = 2450342.883 + 24.64880*E*, e=0.0, γ= –14.09 km s^{-1}, K_1=34.39 km s^{-1}.

2. A model atmosphere analysis of the spectrum of IM Peg has yielded a self-consistent set of fundamental parameters of the primary component: $T_{\rm eff}$=4450 K, log *g*=2.4, [M/H]=0.0, $\xi_{\rm t}$=1.6 km s^{-1}. This corresponds to a K2 III star. The observed abundances of the carbon and nitrogen suggest that the primary has undergone the first convective mixing in its atmosphere on the Red Giant Branch.

3. An unspotted V magnitude of $5\overset{\rm m}{.}55$ was estimated from the observed variation of the TiO band and quasi-simultaneous photometry. The absolute magnitude of the star of $0\overset{\rm m}{.}62$ is found.

4. By combining all parameters, the radius R_1 = 13.3±0.6 $R_\odot$ and the inclination 65°≤ i ≤80° of the primary have been estimated with the assumption that its rotational axis is perpendicular to the orbital plane.

5. The unseen secondary is believed to be a K0 main sequence star with a mass of about 0.8±0.1 $M_\odot$.

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References

Berdyugina S.V., 1991, Izv. Krymsk. Astrofiz. Obs. 83, 102
Berdyugina S.V., 1993, Astron. Lett. 19, 378
Berdyugina S.V., Jankov S., Ilyin I., Tuominen I., Fekel F.C., 1998, A&A 334, 863
Davis S.P., Phillips J.G., 1963, The Red System $(A^2\Pi - X^2\Sigma)$ of the CN molecule. University of California Press, Berkely
Dempsey R.C., Bopp B.W., Henry G.W., Hall D.S., 1993, ApJS 86, 293
Dempsey R.C., Neff J.E., O'Neal D., Oláh K., 1996, AJ 111, 1356
Donati J.-F., Semel M., Carter B.D., Rees D.E., Cameron A.C., 1997, MNRAS 291, 658
Fekel F.C., 1997, PASP 109, 514
Glebocki R., Stawikowski A., 1995 Acta Astron. 45, 725
Hadrava P., 1995, FOTEL3 - user's guide. Astronomical Institute, Academy of Science, Ondrejov
Hall D.S, 1976, In: Fitch W.S. (ed.) Multiple Periodic Variable Stars. IAU Coll. 29, Reidel, Dordrecht, p. 287
Harper W.E., 1920, Publ. DAO 1, 203
Harper W.E., 1935, Publ. DAO 6, 251
Huenemoerder D.P., Ramsey L.W., Buzasi D., 1990, ApJ 350, 763
Ilyin I.V., 1997, Licentiate Dissertation, University of Oulu
Kovacs I., 1969, The rotational Structure in the Spectra of Diatomic Molecules. Academiai Kiado, Budapest
Kurucz R.L., 1993, Kurucz CD No. 13
Kuznetzova L.A., Pazyuk E.A., Stolyarov A.V., 1993, Russ. J. Phys. Chem. 67, 2046
Lambert D.L., 1978, MNRAS 182, 249
Lang K.R., 1992, Astrophysical Data. Springer-Verlag
De Medeiros J.R., Mayor M., 1995, A&A 302, 745
Oláh K., Marik D., Houdebine E.R., Dempsey R.C., Budding E., 1998, A&A 330, 559
Ottmann R., Pfeiffer M.J., Gehren T., 1998, A&A 338, 661
Phillips J.G., Davis S.P., 1968, The Swan System of the C_2 Molecule. University of California Press, Berkeley
Piskunov N.E., Kupka F., Ryabchikova T.A., Weiss W.W., Jeffrey C.S., 1995, A&AS 112, 525
Strassmeier K.G., Bartus J., Cutispoto G., Rodonò M., 1997, A&AS 125, 11
Strassmeier K.G., Hall D.S., Fekel F.C., Scheck M., 1993, A&AS 100, 173