

An estimate of the system parameters in the dwarf nova IP Peg

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Accepted 1986 May 16. Received 1986 May 16; in original form 1986 April 9

Summary. High-speed photometry of the eclipsing dwarf nova IP Peg is used to estimate the geometry of the binary system and the masses of its components. We find a white dwarf eclipse width between 0.0863 and 0.0918, and hence constraints on the mass ratio, q , of $0.35 < q < 0.49$ and on the inclination, i , of $80^\circ.9 < i < 90^\circ$. The white dwarf is surrounded by an extended boundary layer and has a mass of at least $M_{\text{WD}} \sim 0.3 M_\odot$, probably much greater, depending on the thickness of the boundary layer and the orbital inclination. Its mass could be as high as $0.9 M_\odot$ for an inclination of $80^\circ.9$. The mass of the secondary star is greater than $0.09 M_\odot$ probably a lot higher. IP Peg could be earlier in the evolutionary sequence of dwarf novae than the ultra-short-period systems ($P < 2$ hr). The disc radius in our observations is larger than that observed one month previously. This is probably due to the fact that an outburst occurred in the interval between the two sets of observations.

1 Introduction

Cataclysmic variables are short-period binary systems consisting of a cool red dwarf secondary star transferring mass via a gas stream and an accretion disc, on to a white dwarf primary star. A bright spot occurs where the gas stream collides with the disc. Dwarf novae are a sub-class of the cataclysmic variables which undergo short outbursts, of a few days, during which the disc intensity suddenly increases by ~ 3 – 5 mag. This can occur every few weeks or years depending on the system. IP Peg itself brightens by about 3 mag approximately every 100 day.

IP Peg was originally discovered to be a variable by Lipovetskij & Stepanyan (1981). It was then found to be an eclipsing dwarf nova by Goranskij *et al.* (1985) who shows the eclipses to be sharp and deep, and a prominent orbital hump in the light curve. In observations by Goranskij, Lyutyj & Shugarov (1985) the egress of the white dwarf eclipse can also be seen. Schweitzer, Proust & Gunther (1985) have also observed outbursts of IP Peg.

A great deal of information about the geometry of the binary, the structure of the system and the state of the accretion disc can be learned from observations of systems which are so highly inclined to our line-of-sight that the white dwarf, bright spot and disc are all eclipsed. IP Peg is an especially important system since it is the only dwarf nova known with an orbital

period ($P=3$ hr 48 min) above the 'period gap', in which the white dwarf is eclipsed. Cataclysmic variables have a bimodal orbital period distribution, with no systems having periods between approximately 2 and 3 hr (e.g. Robinson 1983). IP Peg will thus provide a good opportunity to study in detail any differences between systems above and below the period gap.

In this paper we present high-speed photometry of six eclipses of IP Peg. We use the data to estimate the geometry of the binary and the masses of its components.

2 Observations and reduction

The observations (summarized in Table 1) were obtained at the 1-m Jacob Kapteyn Telescope at the Roque de Los Muchachos Observatory in La Palma between 1985 November 5–10. An outburst started on JD 2446370 (Mattei, private communication) a few days before our observations. The system was still declining in brightness at the beginning of our observing run. The observations were made, with 1 s integration times, using the La Palma Observatory two-channel People's Photometer with Johnson *V* and *B* filters in channels 1 and 2 respectively.

Table 1.

Journal of Observations

DATE	HJD START	CYCLE	COMMENTS
5 NOV	2446375.39091	4804	ONLY 1ST HALF OF ECLIPSE
6 NOV	2446376.36860	4810 4811	
7 NOV	2446377.35730	4817	ONLY 2ND HALF OF ECLIPSE SOME CLOUDS BUT ECLIPSE UNAFFECTED
8 NOV	2446378.37284	4823	
9 NOV	2446379.38369	4829	

Table 2.

FILTER	EXTINCTION COEFFICIENT (mags/airmass)	E_V (mJy) BD +17 4708
V	0.1057	9.428
B	0.2048	9.730

Measurements of the sky were taken every 5 min, and of a comparison star (66 arcsec west, 19 arcsec south of IP Peg) every half hour, except during eclipse. Two standard stars HD 19445 and BD +17 4708 (Oke & Gunn 1983) were observed several times each night and these observations were used with those of the comparison star to determine the extinction coefficients for the run. The mean values are given in Table 2 and were used to correct the observations to 1 airmass. The range of airmasses observed was between 1 and 1.6. A weighted average of the flux of the standard star BD +17 4708 over each band-pass (listed in Table 2) was used to calibrate the sensitivity of the photometer on each night.

Six eclipses were observed during the run; however, with no guider and using a 14-arcsec aperture the star had to be recentred every 6 min. As recentring required moving the acquisition mirror in and out of view, ~ 1 min of data was lost each time this was done. The recentring had to be done several times during each eclipse and thus many contact points in the eclipses were missed.

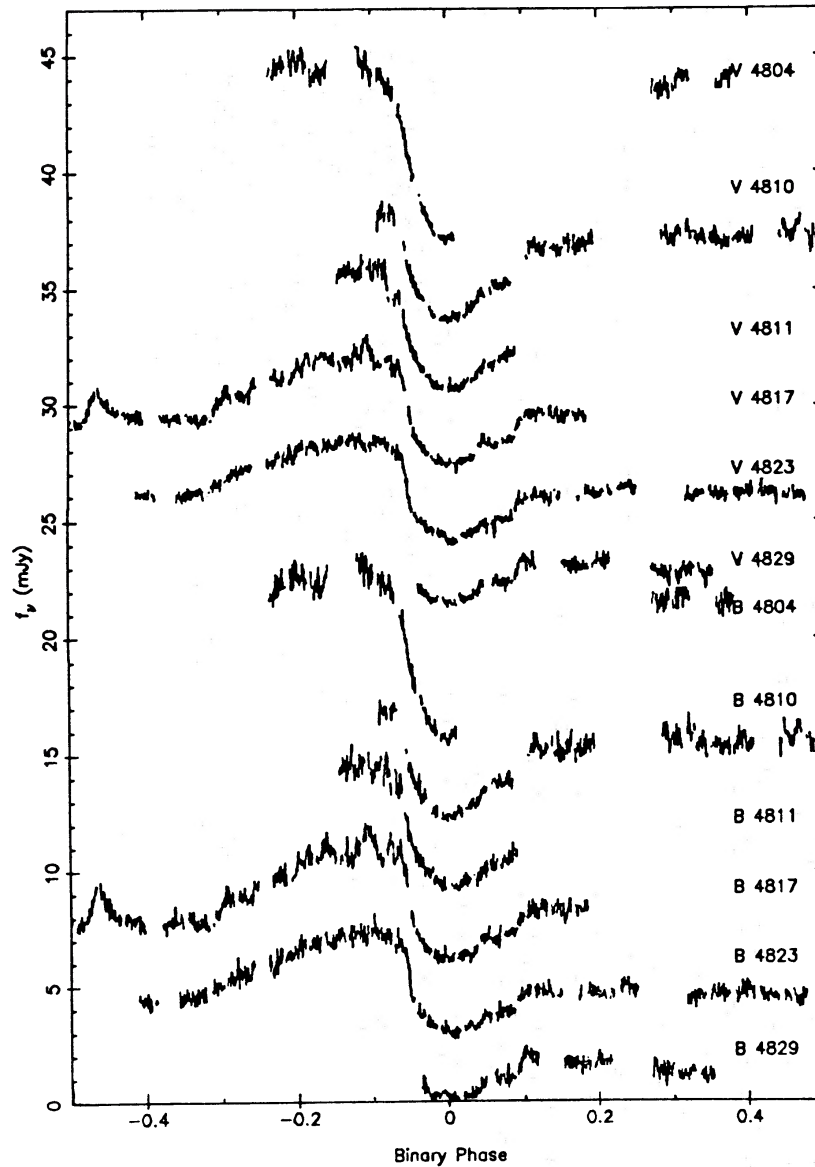


Figure 1. Individual *V* and *B* light curves binned to 10 s time resolution. Each light curve is offset by 3 mJy from the next, with an additional 3 mJy offset between the *V* and *B* light curves. The bottom light curve, cycle 4829 *B*, is at its measured flux density. The phases shown were calculated from the ephemeris in Section 5, with $\beta=0$.

3 Light curves

The individual *V* and *B* light curves are plotted in Fig. 1. The phases shown are those calculated with the ephemeris given in Section 5 (with $\beta=0$). The contact phases of the ingress feature and the bright-spot egress cannot be used to determine the period as they can vary from one cycle to the next if the disc radius changes. The only stable feature is the white dwarf eclipse. The gaps in the data make it impossible to measure most of the contact phases of the eclipse in the individual cycles. In addition the bright spot ingress and egress, much more prominent features than the white dwarf egress, would dominate any results of a period folding analysis. We therefore phase folded the six eclipses using the ephemeris

$$\text{HJD} = 2445615.3940 + 0.15820764E,$$

based on measurements of orbital hump maximum (Goranskij *et al.* 1985). The gaps in the data

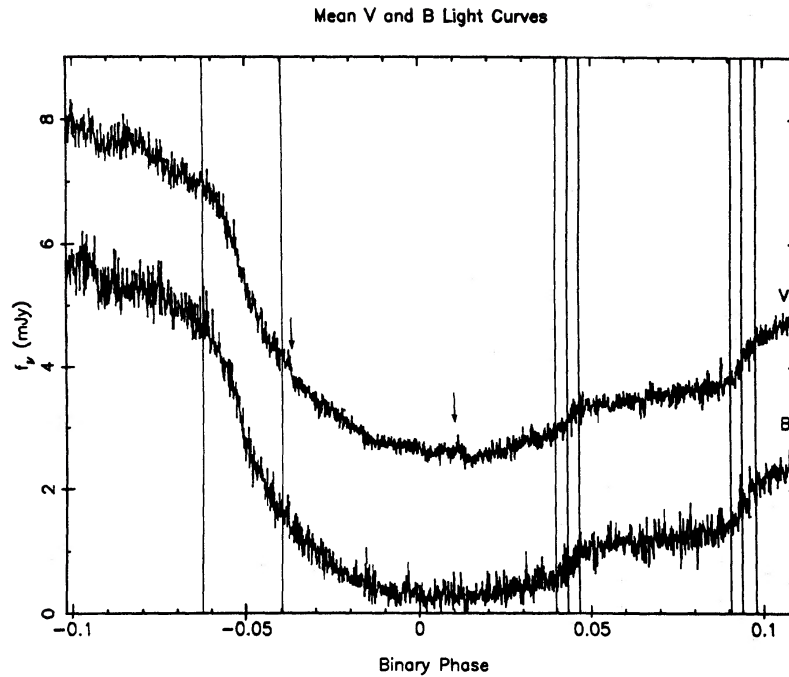


Figure 2. Mean V and B light curves around eclipse, rebinned to 2 s time resolution. The V light curve is offset upwards by 2 mJy. The vertical lines indicate the measured points of contact for the white dwarf and bright spot and the half flux points of each egress. The arrows indicate discontinuities in the mean light curve caused by the end of a data set. The phases shown were calculated from the ephemeris in Section 5, with $\beta=0$.

near eclipse, due to sky measurements and recentring, were filled in by linear interpolation to prevent discontinuities in the mean light curves. However, two such discontinuities remain where only half an eclipse was observed. These points are indicated in Fig. 2 where the mean light curves (V and B) are plotted. Again the phases shown are those calculated with the ephemeris given in Section 5 (with $\beta=0$). The mean eclipse shows well-defined ingress and egress features, indicating that the period we used to fold the data is an adequate estimate of the true period. The ephemeris we used does not give the correct times of zero phase but we will be able to find the correction to zero phase. Since we have effectively only one measurement of the white dwarf egress, however, we cannot find a more accurate period using the present data.

The light curves clearly show a large orbital hump where the bright spot rotates into view from behind the disc, with a single-stepped ingress and a double-stepped egress superimposed on a more gradual disc eclipse. The structure is similar to that of the short-period dwarf novae Z Cha (e.g. Bailey 1979) and OY Car (e.g. Vogt *et al.* 1981) in which the white dwarf, bright spot and disc are all eclipsed. The major difference in IP Peg is that the bright spot and white dwarf ingresses overlap.

4 Geometry of the binary system

The original mean light curves were smoothed using a median filter of width 11 s and a linear (boxcar) filter of width 5 s. This amount of filtering made the ingress and egress features easier to measure, without significantly rounding off their ends. The fact that the two sharp ingress features overlap makes it difficult to measure the phases of the white dwarf ingress (ϕ_{w1} , ϕ_{w2}), but six points of contact were measured straight away from the smoothed mean light curves; the beginning and end of the ingress feature (ϕ_1 , ϕ_2), of the white dwarf egress (ϕ_{w3} , ϕ_{w4}), and of the bright spot egress (ϕ_{b3} , ϕ_{b4}). The half flux points of the two egress

features, ϕ_{we} and ϕ_{be} , were also found using the technique, described in Wood, Irwin & Pringle (1985), to reconstruct the white dwarf (and the bright spot) eclipse from the derivative of the light curve. The measured positions of the six contact phases and the half-flux points of the egress features are shown by vertical lines in Fig. 2. The beginning of white dwarf egress is not well defined and this may cause some error in our measured parameters. A better measurement would require observations of more cycles than we were able to observe, with complete coverage of the eclipses. At some epochs the white dwarf ingress may be separated from the bright spot ingress.

We can find constraints on the binary parameters in the following way. The smallest possible value of the white dwarf eclipse width $\Delta\phi$, where $\Delta\phi = (\phi_{we} - \phi_{wi})/2$ and ϕ_{wi} is the phase of mid white dwarf ingress, occurs when $\phi_2 = \phi_{w2}$, and the largest possible value when $\phi_1 = \phi_{w1}$. Thus, assuming that the white dwarf eclipse is symmetrical about phase zero (the phase of conjunction), i.e. $\phi_{we} = -\phi_{wi}$, we find

$$0.0863 < \Delta\phi < 0.1024.$$

Assuming that the secondary star fills its Roche lobe, for each value of $\Delta\phi$ there is a unique relationship between mass ratio, $q = M_R/M_{WD}$, and inclination, i (Bailey 1979). Thus for each value of $\Delta\phi$ there is a minimum possible value of q , corresponding to an inclination of 90° where the eclipse width is greatest. As $\Delta\phi$ increases this minimum value increases, e.g. for $\Delta\phi = 0.1024$, $q \geq 0.52$ but for $\Delta\phi = 0.0863$, $q \geq 0.28$.

We can further constrain $\Delta\phi$ by requiring theoretical gas stream trajectories (Lubow & Shu 1975) to pass through the position of the bright spot (e.g. Fabian *et al.* 1978; Cook & Warner 1984). This assumes that the stellar orbits are circular and that the secondary star is rotating synchronously with the orbit. In short-period systems, such as IP Peg, this is very likely to be the case.

Each point along the gas stream, for a particular q and $\Delta\phi$, has a unique phase of ingress and egress, and therefore stream trajectories can be plotted on an ingress-phase versus egress-phase diagram. Fig. 3 shows stream trajectories for $\Delta\phi = 0.0863$ and various values of q . It is clear that as q increases the stream trajectories move towards the white dwarf away from the top left corner of the phase-space diagram. In addition, in the light curve, as $\Delta\phi$ increases, phase zero (defined by mid white dwarf eclipse) moves towards the ingress feature making the two observed ingress contact phases less negative and the four observed egress contact phases larger. The observed phases of ingress, (ϕ_1, ϕ_2) , and of bright spot egress, (ϕ_{b3}, ϕ_{b4}) , are shown by a box in Fig. 3. Thus as $\Delta\phi$ increases the position of the box containing the bright spot moves upwards and to the left in the phase-space diagram. Since the smallest possible value of q increases as $\Delta\phi$ increases, and at the same time the bright spot moves towards the top left corner of the phase-space diagram, there is a maximum value of $\Delta\phi$ for which it is only just possible for a stream trajectory to pass through the light centre of the bright spot. We find that this limiting value is $\Delta\phi = 0.0918$. Thus ϕ_1 must be ϕ_{b1} and $0.0863 < \Delta\phi < 0.0918$, i.e. the first ingress contact phase corresponds to the bright spot and not the white dwarf eclipse.

Once a value of $\Delta\phi$ in the allowed range has been chosen we remove the white dwarf eclipse from the mean light curve, using the reconstruction of its egress which we carried out previously, and assuming that its eclipse is symmetrical about phase zero. The position of ϕ_{b2} is measured from the resulting light curve, and the half-flux point, ϕ_{bi} , found. The value of q corresponding to the stream which passes through the light centre (the point corresponding to mid ingress and egress) of the bright spot is then calculated. Using this value of q , the ingress and egress phases of the bright spot give its position, i.e. its distance from the white dwarf, R_D , and its azimuth from the line of centres between the two stars, θ . These phases also give the maximum possible radial (ΔR), azimuthal ($\Delta\theta$) and vertical (ΔZ) extents of the bright spot. All these quantities are defined in Wood *et al.* (1986). As the inclination approaches 90° the constraints on the vertical

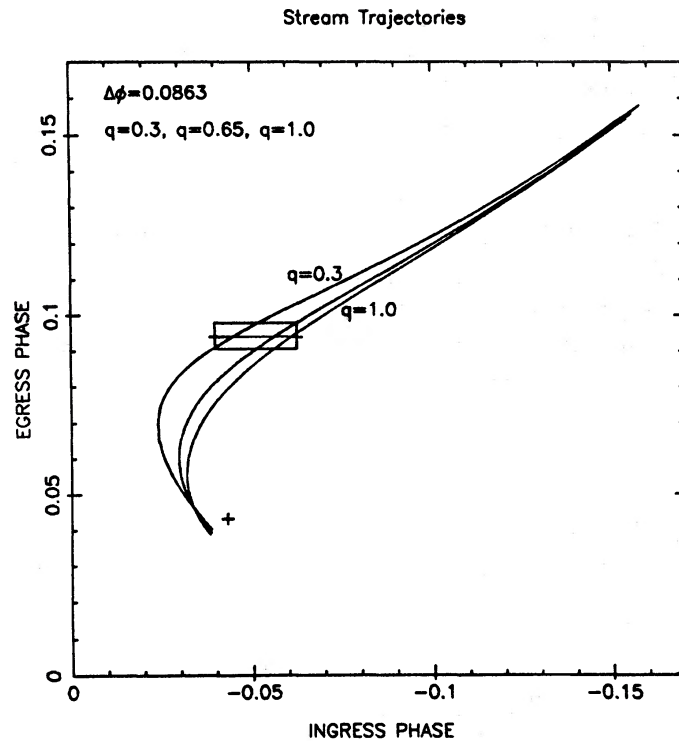


Figure 3. Trajectories of the gas stream from the secondary star, for $q=0.3, 0.65$ and 1.0 with $\Delta\phi=0.0863$, plotted as a function of ingress versus egress phase. The observed position of the white dwarf is shown as '+'. The box edged by the ends of ingress and bright spot egress is shown with mid bright spot egress also indicated. The light centre of the bright spot must lie in this box on the line of mid egress.

extent of the bright spot become very loose and do not give a good measurement of its extent. This is because the phase arcs near $i=90^\circ$ are highly inclined and only cross at a large distance from the plane of the disc.

Assuming that the accretion disc is circular and the bright spot is at its edge, then the radius of the disc is R_D , and the half phase width of its eclipse, $\Delta\phi_{\text{disc}}$, can be calculated and compared to the mean light curve. There is considerable uncertainty in the observed phases of beginning and end of the disc eclipse, since it is a gradual eclipse superimposed on the decline of the orbital hump at the beginning, and ending where we have very little data. For all of our range of values of $\Delta\phi$ the phase widths of the disc eclipse that we calculated were consistent with the observed light curve, although the disc eclipse must begin almost at hump maximum for $i\sim 90^\circ$. Fig. 4 shows the binary system for $\Delta\phi=0.0863$ and our corresponding values of q and R_D . The system looks very similar for $\Delta\phi=0.0918$.

For particular values of q and $\Delta\phi$ the observed duration of the white dwarf eclipse constrains the radius of the central object. The maximum possible radius of a central sphere for $q=0.49$ and $\Delta\phi=0.0863$ is $R_{\text{sph}}=0.017A$ (where A is the orbital separation). The sphere may be surrounded by a flat belt with $R_{\text{belt}}\leq 0.019A$. Different values will be found for other values of q and $\Delta\phi$. For the extreme case where $i\sim 90^\circ$, R_{sph} and R_{belt} are the same. (For a more detailed explanation see Wood *et al.* 1986.) All the measured parameters are listed in Table 3 for each of the extreme values of $\Delta\phi$.

Using Kepler's 3rd law and the Hamada–Salpeter mass–radius relationship for Helium white dwarfs (Hamada & Salpeter 1961), the orbital separation, A , and the mass of the white dwarf, M_{WD} , can be found. This calculation assumes that we know R_{WD}/A . Once A and M_{WD} are known the other system parameters, e.g. M_R and the radial velocities of the two stars, K_R and K_{WD} can

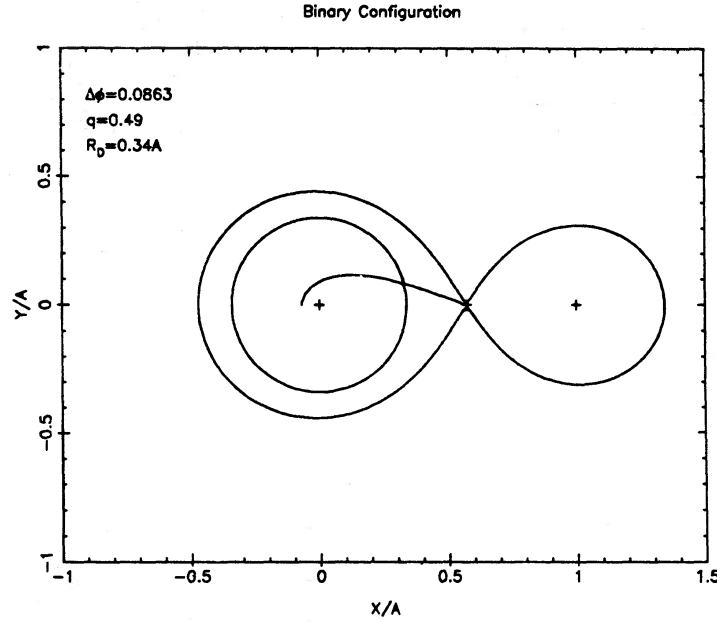


Figure 4. The binary system for $\Delta\phi=0.0863$ and $q=0.49$. The observed positions of the bright spot and white dwarf are also shown with the theoretical gas stream trajectory and a disc of radius $0.34A$.

Table 3. Measured system parameters.

	$\Delta\phi=0.0863$	$\Delta\phi=0.0918$
ϕ_{D1}	-0.0626	-0.0599
ϕ_{D2}	-0.0429	-0.0370
ϕ_{D3}	0.0906	0.0934
ϕ_{D4}	0.0979	0.1007
ϕ_{Di}	-0.0524	-0.0501
ϕ_{De}	0.0939	0.0966
ϕ_{W3}	0.0397	0.0424
ϕ_{W4}	0.0466	0.0493
ϕ_{We}	0.0432	0.0459
q	0.49	0.35
i (°)	80.9	89.5
R_D/A	0.340	0.367
θ	14.2	14.2
$\Delta R/A$	0.028	0.031
$\Delta\theta$	10.9	13.0
$\Delta Z/A$	0.044	0.106
$R_R/R_\odot$	0.301	0.253
$\Delta\phi_{disc}$	0.110	0.117
R_{sph}/A	0.017	0.020
R_{belt}/A	0.019	0.020

also be calculated. The major uncertainty in this stage is that the white dwarf may be surrounded by a large boundary layer, in which case R_{WD} is much smaller than R_{sph} . Martin, Jones & Smith (private communication) have measured a K_R velocity of $\sim 288 \text{ km s}^{-1}$ for IP Peg. This means that there must be an extended boundary layer around the white dwarf; either a spherical one with thickness, H_{bs} , or a flat belt with angular thickness H_{bb} . To obtain the observed value of K_R a very large boundary layer is needed, extending to at least two white dwarf radii. All the calculated parameters are listed in Table 4 for the maximum and minimum possible values of $\Delta\phi$, with various boundary layer thicknesses. The secondary star radius, B_R , is listed in Table 3 for the case where there is no boundary layer.

Table 4. Calculated system parameters.

	$\Delta\phi=0.0863$			$\Delta\phi=0.0918$		
H_{DS}/A	0.000	0.006	0.011	0.000	0.006	0.011
H_{bb}/A	≤ 0.002	0.008	0.013	0.000	0.006	0.011
R_{WD}/A	0.017	0.011	0.006	0.020	0.014	0.009
$M_{WD}/M_{\odot}$	0.30	0.52	0.90	0.27	0.41	0.71
$M_R/M_{\odot}$	0.15	0.26	0.44	0.09	0.15	0.25
K_{WD} (km/s)	98	118	141	72	85	101
K_R (km/s)	200	240	288	203	240	288
$A/10^{10}$ (cm)	6.57	7.88	9.46	5.98	7.06	8.47

5 Preferred parameters and ephemeris

Our range of possible $\Delta\phi$ s gives an ephemeris

$$HJD = 2445615.408432 + 0.15820764E - 0.000428\beta$$

where $0 < \beta < 1$ and $\beta = 0$ corresponds to $\phi_2 = \phi_{w2}$. However, we prefer $\beta = 0$, which corresponds to $\Delta\phi = 0.0863$, to any other value, and have used that value to calculate the phases in Figs 1 and 2.

The reason we prefer this value is that there is some evidence in the mean light curve (after smoothing) that a feature of the correct length to be the white dwarf ingress occurs at the end of the large ingress feature. This feature also showed up in the reconstructed ingress when we tried to measure the half-flux point. After we removed the white dwarf eclipse (for $\beta = 0$) the reconstructed bright spot ingress became smoother. If, however, we used $\beta \neq 0$, meaning that the bright spot eclipse has to continue to ϕ_2 , and removed the white dwarf eclipse the bright spot ingress became more irregular and looked as if it should finish before ϕ_2 .

However, since the signal-to-noise ratio in our data is not very high, and only a few cycles have been folded together we may have been misled by noise or flickering that has not been averaged out. With many cycles folded together the white dwarf ingress should be clearly visible. It may be more easily seen when the system has completely settled down after an outburst.

6 Comparison with systems below the period gap

Fundamental differences between dwarf novae above and below the period gap may give insights into the cause of the gap, and the secular evolution of dwarf novae. Only four systems in which the white dwarf is eclipsed are known with orbital periods below the period gap. Three of these have been investigated without assuming that the observed emission-line K velocity corresponds to K_{WD} , or assuming that the secondary star fits a particular mass–radius relationship, both of which are almost certainly unjustified assumptions. These are Z Cha (Wood *et al.* 1986), HT Cas (Horne, Wood & Stiening, in preparation), and OY Car (Wood *et al.* in preparation).

The assumption that the radius of the white dwarf is approximately given by the length of ingress of the central object, i.e. there is only a thin boundary layer, may not always be correct. The only way of checking this assumption is to measure the radial velocity of the secondary star, K_R . This is very difficult for short-period systems and has only been done for Z Cha and IP Peg. This velocity will not be affected by distortions in the disc, but can be affected by varying brightness over the surface of the secondary star which could be caused by irradiation by the primary. (Usually the actual K_R is slightly smaller than that measured from Na I lines.) In Z Cha, the observed K_R is $\sim 395 \text{ km s}^{-1}$ (Wade & Horne, in preparation), and that predicted from photometric observations is $\sim 370 \text{ km s}^{-1}$ (Wood *et al.* 1986). In IP Peg the difference is much greater, showing that there must be a much thicker boundary layer around its white dwarf. The eclipse of its central object is much less well defined than those of the systems below the period

gap; this could also be due to the extended boundary layer. The nature of this extended layer is not known; it could be a permanent feature perhaps caused by disruption of the inner disc by the magnetic field of the white dwarf, or it could be a temporary feature which formed during the outburst immediately before our observations. Observations well away from an outburst will determine which of these cases is possible.

The mass ratio in IP Peg, $q > 0.35$, is much greater than those of the shorter period systems in which $q < 0.15$. Assuming that there was only a thin boundary layer in the very short-period systems when they were observed, they have secondary star masses $\leq 0.09 M_{\odot}$ and white dwarf masses of $0.5\text{--}0.7 M_{\odot}$. We see that the mass of the secondary star in IP Peg must be greater than in the systems below the period gap; only at $i = 90^{\circ}$, with $R_{\text{WD}} = R_{\text{sph}}$, can its mass be as low. For the observed K_R velocity in IP Peg the white dwarf mass is also larger than those in the shorter period systems.

IP Peg may have originated from a binary with very different initial masses from the other systems, but it is likely that this is part of the evolutionary sequence of cataclysmic variables (e.g. Rappaport, Joss & Webbink 1982). The longer period systems are much younger than the shorter period systems. As the secondary star transfers its mass on to the white dwarf, the mass ratio, q , will decrease. IP Peg may eventually become very similar to Z Cha, HT Cas and OY Car if some mass is lost from the system, e.g. in nova eruptions.

The other major difference between IP Peg and the other systems is the size of its accretion disc relative to the white dwarf's Roche lobe. IP Peg has a much larger disc than the others. However, IP Peg had an outburst just before our observations and this was possibly the cause of the large disc. Observations taken just before the outburst (Marsh, in preparation) show a smaller disc radius. This effect has been seen before in other systems, e.g. Z Cha (Cook 1985; Marsh & Horne, in preparation) and U Gem (Smak 1984).

7 Conclusions

We have found limits in the parameters of the binary with one extreme being our preferred values. These limits are listed in Tables 3 and 4.

(i) We find $0.0863 < \Delta\phi < 0.0918$ corresponding to a mass ratio, q , between 0.35 and 0.49 and an inclination, i , between $80^{\circ}.9$ and 90° . We prefer $q = 0.49$ and $i = 80^{\circ}.9$.

(ii) IP Peg has a much thicker boundary layer around the white dwarf than there is in the eclipsing systems below the period gap. The boundary layer must be thicker than the white dwarf radius for a spherical layer, or extend to more than two white dwarf radii for a flat belt. This layer may be present because the system had just undergone an outburst.

(iii) The secondary star mass is at least $0.09 M_{\odot}$ ($i = 90^{\circ}$), but is probably much larger, $\geq 0.25 M_{\odot}$, if there is a thick boundary layer around the white dwarf.

(iv) The white dwarf mass is at least $0.3 M_{\odot}$, and is probably much larger. Its exact mass depends on the inclination of the system and thickness of the boundary layer. For our preferred inclination and the observed K -velocity of the secondary star, $M_{\text{WD}} = 0.9 M_{\odot}$.

Acknowledgments

We are grateful to Keith Horne, Jim Pringle, Tom Marsh, Jackie Martin, and Derek Jones for helpful comments. We thank the support staff of the Roque de Los Muchachos Observatory in La Palma for their help during the observations. We acknowledge the AAVSO observational data, sent to us by the director, Janet A. Mattei. Reduction and analysis of the photometry was carried out on the Cambridge node of the SERC STARLINK network.

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