RED SPECTROSCOPY OF IP PEGASI

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ABSTRACT. Time resolved spectroscopy of the dwarf nova IP Pegasi in the range λλ 7670-8320Å shows absorption lines originating from the cool secondary. A radial velocity curve for this component has been derived by cross-correlation with a normal M star. The curve has semi-amplitude $K_2 = 288.3 \pm 4$ km s^{-1}, and is slightly distorted. This distortion is equivalent to an orbit with an apparent eccentricity of 0.075 ± 0.024. The mass function of the primary is $0.394 \pm 0.016 M_\odot$. From this we derive constraints on the component masses of $0.62 < M_1 < 1.14 M_\odot$ and $0.17 < M_2 < 0.71 M_\odot$. The red star has a radius in the range $0.32 < R_2 < 0.51 R_\odot$ and is probably on the main sequence.

1. INTRODUCTION

IP Pegasi is a newly discovered variable (Lipovetskij and Stepanyan 1981), which was found to be an eclipsing dwarf nova by Goranskij et al (1985). Wood and Crawford (1985) have carried out high speed photometry showing that the white dwarf is eclipsed in this system, which must therefore have a very high inclination. With a period of 3.8 hours, IP Peg is the only cataclysmic variable above the period gap in which the white dwarf is eclipsed.

2. RADIAL VELOCITY CURVE

IP Peg was observed in September 1985 with the Intermediate Dispersion Spectrograph on the Isaac Newton Telescope at the Roque de los Muchachos Observatory on La Palma. We obtained a resolution of 1.12Å per pixel using a GEC chip, and the total wavelength coverage was 7670-8319Å.

After removal of sky background and atmospheric water absorption, most of the spectra showed characteristic M dwarf absorption features, particularly the NaI doublet at λλ 8183 and 8194Å, which is very strong in M dwarf stars. A radial velocity curve for the secondary was

Paper presented at the IAU Colloquium No. 93 on 'Cataclysmic Variables. Recent Multi-Frequency Observations and Theoretical Developments', held at Dr. Remeis-Sternwarte Bamberg, F.R.G., 16–19 June, 1986.

Astrophysics and Space Science **130** (1987) 145–149.

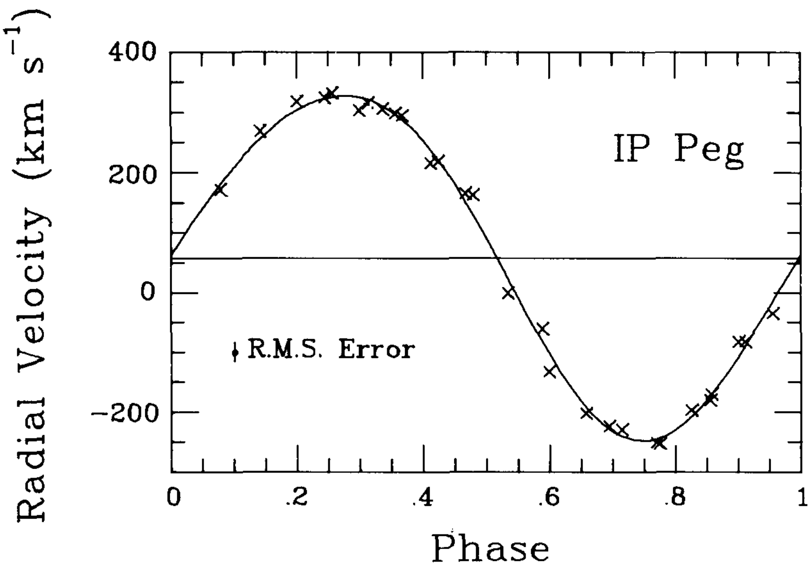

Figure 1. The radial velocity curve of the secondary component of IP Pegasi. The solid curve is a least squares fit to an elliptical orbit showing the slight distortion from a sine curve.

obtained by cross-correlating the spectra with the spectrum of Gleise 83.1, a red dwarf of spectral type M4.5 (Boeshaar, 1976). The results are shown in Fig. 1, together with a least squares fit to a curve of the form

$$V_R = V_0 + S_1 \sin\theta + C_1 \cos\theta + S_2 \sin 2\theta + C_2 \cos 2\theta \quad (1)$$

where θ is the orbital phase calculated from the light elements of Wood and Crawford (1986). The fit to the above curve gave significantly non zero coefficients for the terms in 2θ. In km s^{-1}

$$V_R = 56.7 + 287.0 \sin\theta - 1.37 \cos\theta - 10.4 \sin 2\theta + 19.0 \cos 2\theta \quad (2)$$

The orbital parameters were calculated from this fit using the. method of Russell & Wilsing (Luyten, 1936), which is suitable for orbits of low eccentricity. If the asymmetry of the radial velocity curve were in fact due to an elliptical orbit, the above fit gives an orbit of eccentricity 0.075 ± 0.024. This is not believed to be a true dynamical eccentricity, but due to distortion of the spectra by emission lines from the disc, or heating of the inner face of the secondary.

The data were also fitted to a circular orbit, and parameters calculated from this and the elliptical fit are compared in Table I.

TABLE I

	Elliptical fit	Circular fit
V_0	56.7 ± 3.5 km s^{-1}	56.1 ± 4.3 km s^{-1}
$a_2 \sin i$	$6.25 \pm 0.09 \times 10^5$ km	$6.26 \pm 0.14 \times 10^5$ km
K_2	288.3 ± 4 km s^{-1}	287.7 ± 4 km s^{-1}
$f(M_1)$	$0.394 \pm 0.016 M_\odot$	$0.392 \pm 0.016 M_\odot$
e	0.075 ± 0.024	-
sigma	16.7 km s^{-1}	22.4 km s^{-1}

Sigma is the r.m.s. residual error of the least squares fit in each case. It can be seen that the "elliptical" orbit is the better fit to the data, though the resulting parameters have nearly the same values in each case. Accordingly, we have used the elliptical fit in our calculations.

3. RESULTS

Assuming the white dwarf to be effectively a point object, binary geometry gives

$$r_2/a = \sin^2(\pi\Delta\phi) + \cos^2(\pi\Delta\phi)\cos^2 i \quad (3)$$

(Horne et al, 1982), where i is the inclination, a is the binary separation, $\Delta\phi$ is the phase width of the white dwarf eclipse and r_2 is the projected radius of the secondary at eclipse. We have used $\Delta\phi = 0.0891 \pm 0.0025$ from Wood and Crawford (1986). By assuming that the secondary fills its Roche lobe, we can find the mass ratio $q = M_2/M_1$ as a function of i, using the aproximation given by Eggleton (1983).

$$\frac{R_2}{a} = \frac{0.49\, q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})} \quad (4)$$

R_2 is the radius of a sphere of equal volume as the Roche lobe of the secondary. This is approximately 3% larger than r_2 for the range of q in which we are interested.

From K_2, the semi-amplitude of the radial velocity curve, we obtain the mass function.

$$M_1^3 \sin^3 i/(M_1 + M_2)^2 = 0.394 \pm 0.016 M_\odot \quad (5)$$

Equations (3) and (4) give q as a function of i, and with eqn (5) we find masses for both components. The radius of the secondary, R_2, can also be calculated using $a_2 \sin i$ from the orbital fit. The results are given for different inclinations in Table II, together with predicted values of K_1.

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TABLE II

	$i = 90^o$	$i = 85^o$	$i = 82^o$	$i = 80.9^o$
q	0.31±0.04	0.37±0.04	0.47±0.05	0.53±0.05
$M_1(M_\odot)$	0.68±0.06	0.75±0.08	0.88±0.10	0.96±0.10
$M_2(M_\odot)$	0.21±0.04	0.28±0.06	0.41±0.09	0.51±0.11
$R_2(R_\odot)$	0.33±0.02	0.37±0.02	0.42±0.03	0.45±0.03
K_1(km s^{-1})	90±9	107±13	136±16	153±17

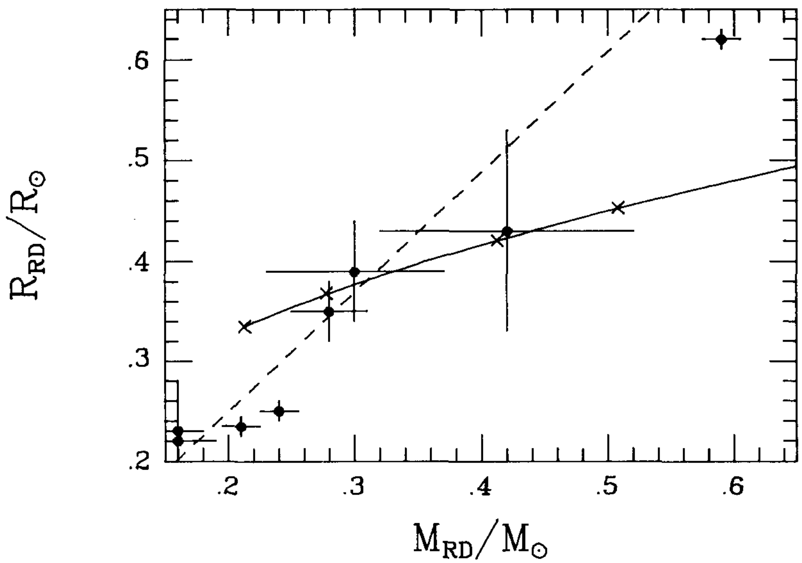

Figure 2. The solid line is the mass radius relation for the secondary star, with crosses marking inclinations of 90°, 85°, 82° and 80.9° from left to right. The heavy points represent low mass stars in detached binaries (Popper, 1980) and the dashed line is a least squares fit to the detached stars, marking the empirical low mass ZAMS (Echevarria, 1983).

4. DISCUSSION AND CONCLUSION

The radial velocity curve of the secondary has a semi-amplitude of 288.3 km s^{-1}. In our calculations, we have not taken into account any heating or distortion effects, which would reduce the magnitude of K_2, thus giving lower masses than the quoted values. With this caveat, we find the lowest possible masses at $i = 90^o$, for which $M_1 > 0.62M_\odot$ and $M_2 > 0.17M_\odot$. Constraints can also be derived from the mass radius relation for the secondary. Fig. 2 shows the possible mass and radius of the secondary in relation to the low mass ZAMS derived from detached

https://doi.org/10.1017/S0252921100104786 Published online by Cambridge University Press

binaries (Echevarria, 1983 and Popper, 1980). It can be seen that the secondary is close the ZAMS for a wide range of inclinations. At lower inclinations, the red star would be smaller than an equivalent mass main sequence star, but this would not be expected in a cataclysmic variable, since the secondary must overflow its Roche lobe. We can use this to place an approximate lower limit on the inclination of $i \gtrsim 80^o$, hence $M_1 \lesssim 1.14M_\odot$ and $M_2 \lesssim 0.71M_\odot$.

From the prominence of the NaI lines we estimate the spectral type of the secondary to be M3-M5. This is supported by the smooth radial velocity curve obtained by cross-correlation with an M4.5 spectrum. For these spectral types we would expect $0.17 < M_2 < 0.33M_\odot$. We do not expect an earlier spectral type since the NaI lines decrease rapidly in strength with increasing effective temperature (Young and Schneider, 1981). Thus for a main sequence secondary, we prefer $i = 83^o$-84^o, for which $M_2 \sim 0.33M_\odot$ and $M_1 \sim 0.8M_\odot$.

The authors thank Janet Wood and Tom Marsh for their help in producing these results.

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