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A spectroscopic study of southern binary Cepheids

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Abstract. High-resolution spectroscopic observations have been made of a number of southern binary Cepheids to determine their dynamical masses. The stars are part of a long-term programme to observe southern variable stars for which a valuable long-term database has been obtained. The most recent radial velocities have a precision of $\sim 300\,\mathrm{m\,s^{-1}}$, allowing the detection of velocity differences of $\sim 1\,\mathrm{km\,s^{-1}}$ with confidence. Masses were determined for three systems: the 9-day Cepheid S Mus ($6.0\pm0.4\,\mathrm{M}_\odot$), the double-mode Cepheid Y Car ($4.5\pm1.8\,\mathrm{M}_\odot$) and the 5-day Cepheid V350 Sgr ($6.0\pm0.9\,\mathrm{M}_\odot$). For five Cepheids (YZ Car, AX Cir, V636 Sco, W Sgr and T Mon) new or improved orbital solutions were found. Line level effects have been observed in several species of lines. Most Cepheids were observed to show the same progression of line level effects. Using non-linear radiative hydrodynamical models, we have compared the results of these models with our observations. These have shown that AX Cir and YZ Car have the following properties: $L = 2050\,\mathrm{L}_\odot$, $M = 4.8\,\mathrm{M}_\odot$, $T_{\mathrm{eff}} = 5900\,\mathrm{K}$ and $L = 9350\,\mathrm{L}_\odot$, $M = 7.7\,\mathrm{M}_\odot$, $T_{\mathrm{eff}} = 5590\,\mathrm{K}$. Our models show no strong shockwaves being produced. Good agreement was found between the observed and modelled spectral lines Fe I 5576Å, Si II 6347Å, Ba II 5853Å and Ca II 8542Å.

1. Introduction

At Mount John University Observatory we have been able to acquire and analyse a significant amount of high-resolution spectroscopic data of Cepheid stars. The data gathered has been used to make line bisector radial velocity measurements of spectral line positions of high precision (Petterson 2002). These data have been applied to hydrodynamical investigations of these objects to better understand the details of line formation in dynamical atmospheres (Albrow & Cottrell 1994, 1996) and in comparison with hydrodynamical models (Fokin 1990).

Our spectroscopic observations are a unique and significant database for work on systems which have orbital periods from one to several years. This is due to the gathering of data using a single instrument and telescope with digital detectors.

To ensure our velocity data is closely linked to the IAU standard radial velocity system a number of radial velocity standard stars were observed. Two or three of these stars were observed on each night that observations were possible. In addition we calibrate our data against telluric lines to improve the absolute velocity scale of our data.

Table 1. Orbital parameters and masses for three binary Cepheids.

Star	S Mus	Y Car	V350 Sgr
Period (days)	504.9±0.1	993±2	1464.9±0.4
eccentricity	0.080±0.002	0.38±0.02	0.45±0.01
K ($\mathrm{km\,s^{-1}}$)	14.7±0.2	8.9±0.3	10.2±0.04
Γ ($\mathrm{km\,s^{-1}}$)	−0.5±0.5	−12.4±0.9	+12.0±0.2
T_0(2400000+)	48590±5	45372±13	47605±1
ω (degs)	206±5	129±17	276±1
f_{mass} ($M_\odot$)	0.166	0.057	0.116
$a \sin i$($\times 10^6$ km)	102	112	183.5
M_{Cep} ($M_\odot$)	6.0±0.4	4.5±1.8	6.0±0.9

Table 2. Orbital parameters for four binary Cepheids.

Star	YZ Car	AX Cir	V636 Sco	W Sgr
Period (days)	657.3±0.3	6532±25	1362±17	1582±9
eccentricity	0.14±0.03	0.19±0.02	0.23±0.01	0.41±0.05
K ($\mathrm{km\,s^{-1}}$)	10.0±0.4	10.0±0.5	12.62±0.09	1.08±0.03
Γ ($\mathrm{km\,s^{-1}}$)	+0.0±0.2	−22.3±0.6	+9.1±0.7	−26.0±0.1
T_0(2400000+)	42250±9	48500±60	34403±3	48286±5
ω (degs)	116±5	231±8	305±5	328±5
f_{mass} ($M_\odot$)	0.066	0.68	0.263	0.157×10^{-3}
$a \sin i$($\times 10^6$ km)	89	907	2300	21.42

2. Results

In Table 1 we present the orbital solutions and dynamical masses for three systems and in Table 2 the orbital solutions for a further four systems determined for seven of the nine systems examined here. T Mon and BP Cir are omitted. Table 3 is a comparison of the masses as derived from: evolutionary theory for a Cepheid on its first crossing of the instability strip and its second crossing on a blue loop; the dynamical mass as determined in this paper; the pulsational mass; and masses from other methods. These masses have been determined by placing the stars (using luminosities and effective temperatures derived from Fernie (1992), Flower (1996), Feast & Walker (1987) and averages from the literature) on theoretical H-R diagrams with evolutionary tracks (Fig. 1, left panel) and isochrones (Fig. 1, right panel).

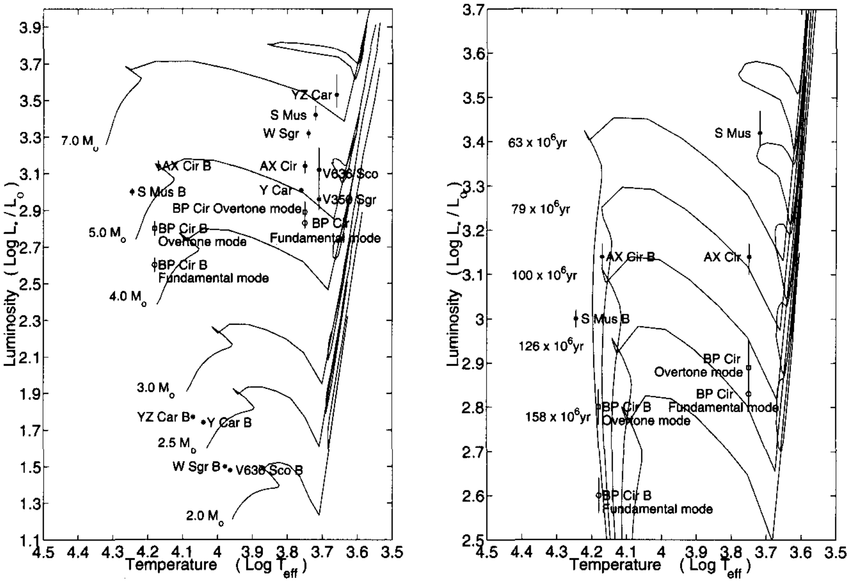

Figure 1. (Left panel) H-R diagram with positions of Cepheids and their companions. The evolutionary tracks are taken from Schaller et al. (1992), with Z=0.02 and 0.2 full pressure scale height overshooting. (Right panel) H-R diagram with the position of the binary Cepheids with evolved companions compared to the isochrones from Schaller et al. (1992). Isochrones are shown for 63, 79, 100, 126 and 158×10^6 yr. The companions for YZ Car, W Sgr, V636 Sco and Y Car fall below the plot and give no information on ages of the systems.

The dynamical masses are more consistent with evolutionary masses associated with Cepheids on blue loops compared to their first crossing (see Table 3). The pulsational masses generally underestimate the dynamical masses.

By examining Cepheid positions on the isochrones (Fig. 1) we see that AX Cir and its companion share a similar age ($100 - 126 \times 10^6$ yr). S Mus is a younger system ($< 63 \times 10^6$ yr). The position of the BP Cir system for its fundamental and overtone modes demonstrates that overtone pulsation gives a similar age for the Cepheid and companion while the fundamental mode does not.

3. Line level effects

Line level effects, the differences between individual species with respect to the gamma velocity of Cepheid pulsations, have been measured in all the Cepheids studied. We observe the existence of line level effects among species, such as Si II and Ba II. The interpretation for the line level effects is the propagation of a pressure wave through the line-forming layers of a Cepheid due to a pulsation. The behaviour of the lines is consistent with Si II lines forming deeper in the

Table 3. Comparison of masses for the Cepheid systems.

M_*	S Mus	Y Car	YZ Car	AX Cir	V636 Sco	V350 Sgr	BP Cir
M_{1st}	7	5	8.7	6	6.2	5.8	5
M_{2nd}	6.3	4.5	7.8	5.0	5.5	5.0	4.5
M_{Dyn}	6.0±.4	4.5±1.8			4.8±.5[3]	6.0±.9	
M_{Pul}	5.2	3.4	6.0	4.2	4.6	4.1	3.7
M_{Oth}		5.0[1]			6[2]	5.8[2]	

[1]Beat mass. [2]Mass from mass-luminosity relation. [3]Böhm-Vitense et al. (1998).

atmosphere and being the first to experience the wave, followed by Fe I, Ba II, Ca II and finally Hα.

4. Models

We can obtain a greater understanding of the physical processes involved in the behaviour of stars by using theoretical models. We present here the results of hydrodynamical modelling of the Cepheids AX Cir and YZ Car. The initial static model parameters were determined using the mass-luminosity relation of Chiosi et al. (1993):

$$\log L/\mathrm{L}_\odot = -0.015 + 3.14Y - 10.0Z + 3.502 \log M/\mathrm{M}_\odot + 0.25$$

Extensive modelling using a non-linear radiative hydrodynamical code (Fokin 1990) and the latest OP opacities has determined that AX Cir and YZ Car have the following properties: $L = 2050\,\mathrm{L}_\odot$, $M = 4.8\,\mathrm{M}_\odot$, $T_{\mathrm{eff}} = 5900\,\mathrm{K}$ and $L = 9350\,\mathrm{L}_\odot$, $M = 7.7\,\mathrm{M}_\odot$, $T_{\mathrm{eff}} = 5590\,\mathrm{K}$ respectively. We have compared the results of these models with our observations and good agreement was found between the observed and modelled spectral lines Fe I, Si II, Ba II and Ca II.

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