The Mass of the Beat Cepheid Y Carinae

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Abstract. With the HST and the GHRS, we measure on two adjacent spectra the radial velocity of the B9 V companion to the beat Cepheid Y Car. The orbital-velocity ratio for the Cepheid and its companion gives a preliminary mass ratio of $M_{\text{Cephe}}/M_{\text{B9}} = 1.55 \pm 0.2$, yielding a preliminary mass of $4.0 \pm 1M_{\odot}$ for the Cepheid.

1. Introduction

Y Car is one of the beat Cepheids which have puzzled astronomers for decades because the measured period ratios around 0.71 implied masses between 1 and 2 solar masses, when conventional models (Becker 1981) and Cox & Tabor (1976) opacities are used. On the other hand, the lengths of their periods implied so-called pulsational masses around 3.5 solar masses and their evolutionary masses, derived from fitting their luminosities on the blue loops of standard evolutionary tracks of evolved stars, indicate masses around 5 solar masses. If, however, evolutionary tracks with excess mixing, for instance, due to convective overshoot (Bertelli et al. 1986) are used, the evolutionary masses can be reduced by about 1.5 solar masses. Simon (1982) suggested that the opacities in layers with temperatures around $5 \times 10^5$ K are higher by a factor of about two than the Cox-Tabor opacities. The new Livermore, OPAL, opacities (Iglesias & Rogers 1990) are indeed higher and masses around $4 M_{\odot}$ can be obtained from the observed period ratios of beat Cepheids (Moskalik, Buchler & Marom 1992). It seems quite important to determine the degree of excess mixing in the cores of main-sequence stars and also to confirm the Livermore opacities by determining the dynamical mass of a beat Cepheid.
2. The Orbit of the Cepheid Y Carinae A

The orbital period was determined by Balona (1983) to be 993 days. Since then Berdnikov (1992) has determined \( P_0 \) and \( P_1 \) from all the photometry available. With these data and the data provided by Balona (1983) and sources therein, one of us (N. E.) determined a new period of \( 1006.9 \pm 11 \) days. The new orbit determination reduces the standard deviation to 3.8 km s\(^{-1}\). The system velocity, \( \gamma \), was determined to be \(-12.9 \pm 0.4 \) km s\(^{-1}\) and \( K = 10 \) km s\(^{-1}\).

3. The Radial Velocities of Y Car B

On 1993 June 24, the spectrum of Y Car B was observed with the Hubble Space Telescope, using the GHRS with the G200M grating centered at 1860 Å. This gives a resolving power \( \lambda/\Delta \lambda = 20,000 \) corresponding to \( \Delta \lambda \sim 0.1 \) Å. The spectrum covers a wavelength band of 32 Å. The 2'' aperture was used to keep the exposure times within reasonable limits. The exact centering was assured by the PEAKUP procedure. Two 25-minute exposures were broken up into 5-minute subexposures. A wavelength calibration was taken at the beginning and at the end of each 25-minute exposure. For each 25-minute exposure the five subexposures were then superimposed to give two spectra.

The cross-correlation of the combined Y Car spectrum with a synthetic spectrum for 10,000 K gave a velocity difference of \(-25 \) km s\(^{-1}\). We also obtained a spectrum of \( \alpha \) Lyrae. The velocity zero point was determined from 15 individual lines. The cross-correlation between the Y Car B and the \( \alpha \) Lyrae spectra gave a velocity for Y Car B of \(-22.2 \) km s\(^{-1}\). The average of these two velocities yields \( v_\tau \) (Y Car B) = \(-23.6 \) km s\(^{-1}\). The cross-correlation of the two 25-minute exposures showed a velocity difference of 2.9 km s\(^{-1}\), which may be attributed to independent centering in the entrance aperture. We may then guess that the centering uncertainty for these spectra is perhaps \( 3 \) km s\(^{-1}\).

4. The Mass of the Beat Cepheid Y Car A

From the Cepheid orbit we find that at the time of observation for Y Car B the Cepheid had an orbital velocity of \(+6.9 \pm 0.6 \) km s\(^{-1}\).

If we can use the average velocity of \( v_\tau = -23.6 \) km s\(^{-1}\) for Y Car B, the orbital velocity for Y Car B at the time of observation was \(-10.7 \) km s\(^{-1}\), and the ratio of the orbital velocities was \( 1.55 \pm 0.2 \), which gives the mass ratio. Adopting a centering uncertainty of \( 3 \) km s\(^{-1}\) the error limit for this ratio becomes 0.5.

The Cepheid companion, Y Car B, was observed with the IUE satellite by Evans (1992). The comparison of the dereddened energy distribution of Y Car B for \( 1220 < \lambda < 2000 \) Å with those of standard stars of known spectral types, indicates a spectral type of B9 V for Y Car B.

According to Andersen (1990) the mass of a main-sequence B9 V star with \( B - V = -0.06 \) is \( 2.6 \pm 0.1 \) \( M_\odot \). With the mass ratio adopted above we find for the mass of the Cepheid \( M = 4.0 \pm 1.1 \) \( M_\odot \). With the average centering uncertainty of \( 6.5 \) km s\(^{-1}\), the uncertainty in the mass increases to \( \pm 2M_\odot \).
Figure 1. Plotted are the stellar luminosities at the tip of the blue loops for different stellar masses and for different evolutionary tracks. Also plotted are the mass-luminosity relations for binary Cepheids for which dynamical masses have been determined. The point for V636 Sco is based on somewhat uncertain IUE data. SU Cyg is a triple system studied by Evans & Bolton (1988). The S Mus, Y Car, and V350 Sgr points are based on GHRS data.

This mass determination is based on only two adjacent spectra at one orbital phase. Another spectrum, taken at the phase of minimum orbital velocity for the Cepheid, was very noisy and no reliable orbital velocity could be measured. The mass determination for Y Carinae must therefore be considered to be only preliminary.

From the Schmidt (1984) P–L–C relation we derive $M_V = -2.83$ and $\log L/L_\odot = -3.03$ for the Cepheid. Adopting $M_V = 0.5$ for a B9 V star, one finds $M_V = -3.3$ for the Cepheid and $\log L/L_\odot = 3.22$. We adopt $\log L/L_\odot = 3.1 \pm 0.12$ for the Cepheid Y Car A.

5. Summary and Discussion

In Figure 1 we have plotted the mass-luminosity relation for the tips of the blue loops as obtained theoretically by Becker (1981) from evolutionary tracks with no convective overshoot mixing, from tracks by Maeder & Meynet (1988) with overshoot mixing by 1/2 pressure scale height, and from tracks by Bertelli et al. (1986) with convective overshoot mixing by 1 pressure scale height.

If we take the derived mass value for Y Car A at face value it does, according to Figure 1, indicate excess mixing in the interior of its main-sequence progenitor intermediate between the value assumed by the Bertelli et al. and the Maeder & Meynet evolutionary tracks.
The derived mass is in the mass range obtained for beat Cepheids from the ratio of their beat periods, when the OPAL opacities are used for the stellar models. It thus shows that the higher opacities are correct, provided this mass value can be confirmed.

In Figure 1 we have also entered the mass value for V350 Sgr obtained in the same way, see Evans et al. (this Volume). Its companion is a rapid rotator and the velocity measurements are therefore not very accurate. While for all three stars, S Mus, Y Car, and V350 Sgr the error limits for the mass determinations are large, and for Y Car the value must be considered as only preliminary, the agreement between the results for these three stars gives us, however, some confidence that the values are not far from the truth. This means the degree of excess mixing in main sequence stars with masses around 5 solar masses probably corresponds to overshoot mixing by about 0.7 pressure scale heights. SU Cyg is a triple system. Its dynamical mass, as determined by Evans & Bolton (1988), indicates no excess mixing.

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**References**

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