THE DYNAMICAL MASS OF THE BEAT CEPHEID Y CARINAE AND STELLAR OPACITIES†

E. BÖHM-VITENSE
Department of Astronomy, Box 351580, University of Washington, Seattle, Washington 98195
Electronic mail: erica@astro.washington.edu

N. R. EVANS
Harvard Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138
Electronic mail: evans@cfambl.harvard.edu

K. CARPENTER
Goddard Space Flight Center, Code 681, Greenbelt, Maryland 20771
Electronic mail: hrscarpen@tmal.gsfc.nasa.gov

S. MORGAN
University of Northern Iowa, Cedar Falls, Iowa 50614
Electronic mail: siobahn.morgan@uni.edu

B. BECK-WINCHATZ
Department of Astronomy, Box 351580, University of Washington, Seattle, Washington 98195
Electronic mail: bbeck@astro.washington.edu

R. ROBINSON
Computer Science Corporation, NASA/GSFC, Code 681, Greenbelt, Maryland 20771
Electronic mail: hrsrobinson@tmal.gsfc.nasa.gov

Received 1997 March 13, revised 1997 May 27

ABSTRACT

The beat Cepheid, Y Carinae A, has a B9 V companion, Y Car B. The primary period \( P_0 \) of the Cepheid is 3.64 days and the secondary, \( P_1 \), is 2.56 days. Its period ratio \( P_1 / P_0 \) is thus 0.703. Y Car is the only beat Cepheid known to be a binary and thus offers us the unique opportunity to determine the dynamical mass for a beat Cepheid. We have determined its mass by measuring the orbital velocity amplitude of the hot companion Y Car B using the Goddard High-Resolution Spectrograph (GHRS) with the G200M grating on the Hubble Space Telescope. When combined with the ground-based orbital velocity amplitude of the Cepheid and the mass of the companion, the implied mass of the Cephieid is 3.8± 1.2 \( M_\odot \). With the Cepheid luminosity given by the period–luminosity relation, this mass, taken at face value, indicates excess mixing in the main sequence progenitor corresponding to convective overshoot by about 0.9 pressure scale height, however, the large error bars prevent a firm conclusion. As shown by Simon the period ratio for beat Cepheids depends sensitively on the opacities. For models calculated with Cox–Tabor opacities the period ratios for beat Cepheids indicate masses between one and two \( M_\odot \). Models calculated with the new Livermore OPAL opacities on the other hand indicate masses around 4 solar masses. The good agreement of the beat mass with the dynamical mass, determined here for Y Car, provides a confirmation that the OPAL opacities are a significant improvement over the Cox–Tabor (1976) opacities. © 1997 American Astronomical Society. [80004-6256(97)01109-6]

1. INTRODUCTION

Y Carinae 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 (Stobie 1977), when conventional models (Becker 1981; Becker et al. 1977) and Cox–Tabor (1976) opacities were used. On the other hand, the lengths of their periods implies so-called pulsational masses around 3.5 solar masses (Cox 1980) and their evolutionary masses indicated masses around 5 \( M_\odot \) when standard evolutionary tracks were used.

In the last decade possible solutions to the mass discrepancy have been offered. If evolutionary tracks with strong excess mixing, for instance due to convective overshoot (Bertelli et al. 1986) are used, the evolutionary masses can be reduced to about 3.5 solar masses. In 1982 Simon suggested that the opacities in layers with temperatures around 4 – 6 electronvolts are important.
10^5 K are higher by a factor of 2 than the Cox–Tabor opacities. The new, higher Livermore opacities, the OPAL opacities, (Iglesias & Rogers 1990) are indeed higher by about the suggested amount, and masses around 4 solar masses can be obtained from the period ratios (Moksalik et al. 1992). The question then is, are the masses of the beat Cepheids indeed around 4 solar masses, thereby confirming excess mixing in their interiors and also confirming the new opacities?

In order to check this we have determined the dynamical mass of Y Carinae, the only known binary beat Cepheid, (Stobie & Balona 1979). The dynamical mass determination is independent of evolution and pulsation theory, and therefore offers a check on both these theories.

2. The Properties of Y Carinae B

The companion to the Cepheid, Y Car B, was observed with the IUE satellite by Evans (1992). In an iterative process, both the spectral type of the companion and the Cepheid colors, corrected for the effect of the companion, were derived. This involved using the reddening relations of Dean et al. (1978) to derive E(B−V) = 0.08 from the corrected colors, which was then used to deredden the observed spectrum. For 1200 < λ < 2000 Å Evans then compared the dereddened spectrum with those of standard stars of known spectral types. The best match occurred for a B9 V star. According to Andersen (1991) a B9 V star has a mass of 2.6 ±0.1 M⊙ (Evans & Sugars 1997). The small uncertainty results primarily from the high precision with which spectral types in this range can be determined from IUE spectra.

Assuming for a B9 V star an absolute magnitude of M_V = 8.86, Evans derived a distance modulus for the binary system of 10.79. With M_V = 0.5, which is perhaps more appropriate for a B9 V star, considering that this is the absolute magnitude of the A0 V star α Lyrae, the distance modulus increases to m−M = 11.15. The distance modulus derived from the period–luminosity–color relation is 10.94, including the correction for the companion (Fernie et al. 1995).

3. The Spectroscopic Properties of the Cepheid

3.1 The Effective Temperature of the Cepheid

Y Carinae A

The average T_eff of Y Car A can be obtained from its average (B−V)_0 color. With E(B−V) = 0.08 Evans obtained an average (B−V)_0 = 0.56 which is correct for the companion, leading to T_eff = 5800 K (Böhm-Vitense 1981, see also Teays & Schmidt 1987). Comparison with the (B−V) vs T_eff relation from δ Cep as discussed by Evans & Teays (1996, using the correction from Fernie (1990) for the type of color average used) results in (B−V) = 0.52 mag and T_eff = 6170 K. (Böhm-Vitense 1981 gives 5970 K for supergiants with this B−V.)

3.2 The Luminosity of the Cepheid

For the given period of 3.64 days we can fit Y Car A on the period–luminosity relation for the fundamental mode or first overtone pulsators. Based on the Feast & Walker (1987) data and the dM_V/d log P = −2.9 generally adopted by Freedman & Madore (1991), we find M_V = −2.8. Feast & Catchpole (1997) have suggested increasing the Cepheid distances on average by 10% based on Hipparcos parallaxes. (For Y Car the absolute magnitude computed from the Feast and Walker PLC relation is 0.01 mag fainter than that computed from the Feast and Catchpole PL relation, which is M_V = −3.0 mag.)

The average apparent magnitude of the Cepheid is V_0 = 7.85. With the distance modulus m−M = 10.79, this leads to M_V = −2.94, as derived by Evans. With the larger distance modulus of 11.15 we find M_V = −3.3. From the Schmidt (1984) P–L–C relation we derive for (B−V)_0 = 0.56 that M_V = −2.84. For (B−V) = 0.52 we find M_V = −2.95. We adopt m_V = −3.0±0.15 leading to log L/L⊙ = 3.10±0.06.

4. The Dynamical Mass of the Cepheid

The orbital velocities of the Cepheid can be determined by ground-based observations. The data used are those provided by Balona (1983) and the sources he cites. The orbit derived by one of us (N.R.E.) is a refinement of his in two ways. First, Berdnikov (1992) has recently determined P_1 and P_2, the fundamental and first overtone periods from all the photometry available. Second, Balona corrected for the pulsation velocities using two sine waves to represent the two periods. We have solved simultaneously for the orbit and a pulsation curve represented by 6 Fourier terms. The program used was the least-squares routine used by Evans et al. (1990). The Fourier coefficients are similar to those found by Stobie & Balona (1979). These improvements have reduced the standard deviations from 5.3 to 3.8 km/s (per point) in our solution. Table 1 lists the orbital parameters. Figure 2 shows the orbital solutions and the measured orbital velocities.
In order to determine the orbital radial velocities for the companion, Y Car B, we obtained two spectra for this star using the Hubble Space Telescope (HST) with the Goddard High-Resolution spectrograph (G HRS) and the G200M grating, centered at 1860 Å. This gives a resolving power of 20,000, corresponding to 0.1 Å at 1860 Å. The exact centering in the large science aperture (LSA, 2") for the first spectrum, and in the small science aperture (SSA, 0.25") for the second spectrum was assured by a PEAKUP procedure. The spectrum covers a wavelength band of 39Å. The first spectrum was obtained on 1993 June 24 before the First HST Servicing Mission. The second spectrum was obtained on 1994 April 18 after the servicing mission. For the first spectrum, two 25 min exposures were obtained back to back, each broken up into 5 subexposures in order to reduce geomagnetic smearing. These were then corrected for wavelength shifts, using wavelength calibrations before (first subexposure) and after the stellar spectrum (last subexposure). Finally, all the segments were added.

For the first spectrum the two exposures were centered independently by the PEAKUP procedure. The velocity difference between them was determined by cross-correlation and came out to be 2.9 km/s. This difference gives us some estimate of the uncertainty in the velocity measurement due to the centering uncertainty. Its relatively small value gives us confidence that the target was accurately centered in the LSA. We will use this value in estimating the accuracy of the stellar velocity.

The second spectrum of Y Car B was taken near maximum orbital velocity for Y Car B. Our requested observations, however, were altered because of surrounding target of opportunity observations. Two 25 min exposures had dedicated wavelength calibrations but only at the beginning of the exposures, which were again taken in 5 min parts. The target centering is better than for the first observations because the small science aperture (SSA) was used. On the other hand, the flux was reduced for the same reason. The spectra therefore are very noisy. The centering uncertainty for the second SSA spectrum is taken to be 2.7 km/s as given by Heap et al. (1995).

The noise in the second spectrum made it very difficult to obtain a velocity difference between the spectra taken at minimum and maximum orbital velocity. Because of this we have measured velocity differences with respect to velocity standard star spectra, which are less noisy. We obtained spectra of two standards with the same instrumental setup, α Lyrae and HD 72660. α Lyrae obliterated the wavelength calibration spectrum with stellar light, so the spectrum lacked a wavelength zero point. HD 72260 is an Al V star with a very low rotation. Its velocity is 2.9±0.2 km/s, based on observations by Fekel (1996) using 68 Tau as a comparison star.

Experience gained with the Y Car spectra indicated several possible problems in the velocity determination. First, because we are working with only 40 Å of spectrum, the relatively small number of lines means that the spectrum of a star with only slightly different spectral type can be different enough to give a somewhat different velocity when used as a correlation standard. This was demonstrated by the correlations of each half of the wavelength range of the α Lyra and HD 72660 spectra. The velocities were found to differ by an amount comparable to the centering uncertainty, inspite of the high signal to noise of the spectra. A second source of error is a difference in rotation velocity between the two stars. The importance of this error was estimated by convolving the two sharpened standard star spectra with rotational broadening functions for 50 and 100 km/s. The velocity difference for the unbroadered spectra was 13.9 km/s (HD 72660—α Ly) but 15.5 km/s for the spectra broadened by 100 km/s.

For these reasons it is highly desirable to measure the velocity difference from two identical spectra shifted in velocity by orbital motion. The two Y Car B observations were, however, difficult to correlate, presumably because of the high noise, particularly in the second spectrum, distorting the features in the small wavelength region. We therefore use the velocities derived using the higher signal to noise standard star spectra as templates.

Table 2 summarizes the results, including the data and orbital phases of the observations and the orbital velocities of the Cepheid from the orbital data given in Table 1. Inspection of the two standard star spectra convolved to different rotational velocities showed that a rotational broadening of 100 km/s gives a spectrum most similar to the Y Car B spectra. We give the results for this broadening in Table 2. Columns 2 and 3 list the differential velocities relative to the
Table 2. Measured velocities for (a) Y Car A and (b) Y Car B.

<table>
<thead>
<tr>
<th></th>
<th>V(α Lyr)</th>
<th>V(Y Car)</th>
<th>V(Y Car)</th>
<th>Orb V</th>
<th>Orb V</th>
<th>Orb V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>km/sec</td>
<td>km/sec</td>
<td>km/sec</td>
<td>km/sec</td>
<td>km/sec</td>
<td>km/sec</td>
</tr>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
<td>(7)</td>
</tr>
<tr>
<td>V1</td>
<td>49162.81</td>
<td>49162.81</td>
<td>-0.4</td>
<td>-2.1</td>
<td>4.9</td>
<td>10.8</td>
</tr>
<tr>
<td>V2</td>
<td>49461.29</td>
<td>49461.29</td>
<td>-12.8</td>
<td>-8.0</td>
<td>-20.5</td>
<td></td>
</tr>
</tbody>
</table>

*a: Velocities of Y Car A
b: Velocities of Y Car B

Table 2(b) lists the two differences between the Y Car spectra near orbital velocity maximum and minimum derived from the two standard star templates. The mean difference is 29.2 km/s with a mean error of ±2.0 km/s. Also given are the orbital velocities for the two observations (columns 6 and 7). While it is possible to derive individual masses from these velocities, the results are highly divergent. It is clear that the velocity differences (columns 2 and 3) are more accurate than the individual velocities because they depend less on differences in temperature and rotational velocities of the comparison stars. We will therefore use these velocity differences in the rest of this discussion.

Realistic errors are difficult to quantify, because we have only two spectra with limited wavelength coverage. When cross-correlating spectra from the same star the dominant source of error is the aperture centering error. (See also Böhm-Vitense et al. 1997b; Evans et al. 1997a, and Evans et al. 1997b for the discussions of the V636 Sco, V350 Sgr, and U Aql systems, respectively.) This error has been determined by Heap et al. to be 2.7 km/s for the SSA, G200M observations. We have argued above that even though the first Y Car spectrum was taken through the LSA, internal evidence indicates that the centering uncertainty was the same as for the SSA exposure. In the case of Y Car B there are additional uncertainties, because we had to take the intermediate step to compare the Y Car spectra with comparison star templates, which may differ from Y Car in temperature and rotational velocity. Additional uncertainty is caused by the weakness of the second spectrum. (It actually looks somewhat different from the first one presumably due to noise.) How much this can affect the derived orbital velocities can be seen from the difference in velocities for the second spectrum, depending on which comparison template.
Theoretical ratios are slightly larger than the theoretical one in steps of 100 K. As indicated the points with the refer to different \( r_{\text{eff}} \). Theoretical ratios \( P_0 \) as a function of \( \log \frac{L}{L_\odot}/P_0 \) for stars with 5 \((A)\), 4 \((X)\), and 3\((\ast)\) solar masses, and with solar abundances, as calculated by one of us (S.M.). The model calculations use the OPAL opacities. The different points refer to different \( T_{\text{eff}} \) in steps of 100 K. As indicated the points with the refer to the lowest temperature. The highest temperature being lower than the one observed for Y Car. For masses lower than 4 \( M_\odot \) appear to be excluded, because their fundamental mode periods are larger than the observed one.

For the mass of 4 solar masses the required \( \log \frac{L}{L_\odot} = 3.05 \) and \( T_{\text{eff}} = 5930 \) K are well within the empirical error bars. For luminosities larger than \( \log \frac{L}{L_\odot} = 3.1 \) no mass and \( T_{\text{eff}} \) can be found to give the correct period and period ratio.

We wonder whether for somewhat different metal abundances than the solar ones, which we used so far, we might find a different beat mass for Y Car. One of us (S.M.) studied this question for heavy element abundances reduced by a factor of 2 as compared to the solar ones. The results are shown in Fig. 5, where we have plotted \( \Delta \) the possible luminosities as a function of mass. These luminosities provide the \( P_0 \) and \( P_1/P_0 \) observed for Y Car. For the lower heavy element abundances there is only one luminosity for each mass that gives the correct periods. Figure 5 shows that for all the models studied the required luminosities are much higher than the observed one and the same is true for the temperatures. It thus appears that Y Car must have heavy element abundances, which are very close to the solar ones.

![Figure 3](image-url)  
*Fig. 3.* In the "Petersen" diagram we have for \( \log \frac{L}{L_\odot} = 3.0 \) plotted the theoretical ratios \( P_1/P_0 \) as a function of \( \log P_0 \) for stars with 5 \((\Delta)\), 4 \((\times)\), and 3\((\ast)\) solar masses, and with solar abundances, as calculated by one of us (S.M.). The model calculations use the OPAL opacities. The different points refer to different \( T_{\text{eff}} \) in steps of 100 K. As indicated the points with the refer to the lowest temperature. The highest temperature being 6500 K. The position of Y Carinae in this diagram is indicated by the open circle. The agreement between the observed and calculated period ratio for Y Car with \( \Delta = 3.8, M_\odot \) is quite good, confirming the validity of the OPAL opacities.

![Figure 4](image-url)  
*Fig. 4.* The theoretical lengths of the fundamental periods are plotted as a function of \( \log \frac{L}{L_\odot} \) for temperatures of 6100 K \((\times)\) and 5800 K \((\ast)\) for the 4 \( M_\odot \) models. For a temperature of 5900 K the observed period is obtained for \( \log \frac{L}{L_\odot} = 3.05 \).

![Table 3](image-url)  
*Table 3.* Possible combinations of \( L \) and \( T_{\text{eff}} \) to give the observed period \( P_0 \) and period ratio \( P_1/P_0 \).

<table>
<thead>
<tr>
<th>Mass/( M_\odot )</th>
<th>( \log \frac{L}{L_\odot} )</th>
<th>( T_{\text{eff}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.75</td>
<td>2.78</td>
<td>5490</td>
</tr>
<tr>
<td>2.75</td>
<td>3.05</td>
<td>6380</td>
</tr>
<tr>
<td>3.0</td>
<td>2.82</td>
<td>5520</td>
</tr>
<tr>
<td>3.0</td>
<td>3.05</td>
<td>6290</td>
</tr>
<tr>
<td>3.25</td>
<td>2.86</td>
<td>5550</td>
</tr>
<tr>
<td>3.25</td>
<td>3.06</td>
<td>6210</td>
</tr>
<tr>
<td>3.5</td>
<td>2.90</td>
<td>5580</td>
</tr>
<tr>
<td>3.5</td>
<td>3.06</td>
<td>6120</td>
</tr>
<tr>
<td>3.75</td>
<td>2.95</td>
<td>5590</td>
</tr>
<tr>
<td>3.75</td>
<td>3.04</td>
<td>5980</td>
</tr>
<tr>
<td>4.0</td>
<td>3.05</td>
<td>5980</td>
</tr>
</tbody>
</table>

© American Astronomical Society • Provided by the NASA Astrophysics Data System
The mass found here for Y Car A is compatible with the luminosity-temperature combination found by Simon & Kanbur (1994) (their Fig. 7).

6. THE DEGREE OF MIXING IN THE INTERIOR OF THE MAIN SEQUENCE PROGENITOR OF Y CAR A

We expect the Cepheid to be on a blue loop crossing through the instability strip. We do not know whether it is on the second or third crossing. The stars have, however, a large chance to be near the tip of the blue loops. In Fig. 6 we have therefore plotted the luminosities of the tips of the blue loops as a function of mass for three different sets of models with different degrees of excess mixing. Fitting the luminosity of Y Car on this plot we expect for the Bertelli et al. models (with large excess mixing) a mass of 4.0 M☉, for the Maeder and Meynet models with an intermediate degree of mixing a mass of 4.4 M☉, and for the Becker models with no excess mixing a mass of 5.3 M☉. The probable dynamical mass of 3.8 ± 1.2 M☉ for Y Car A, which we determined here, if taken at face value, puts Y Car very close to the Bertelli et al. models. Of course, we have to remember that the error limits for this determination are ±1.2 M☉, however, the beat mass determined from the period ratio also puts it close to the Bertelli et al. tracks, indicating an excess mixing for the Y Car main sequence progenitor corresponding to convective overshoot mixing by about 0.9–1 pressure scale height. In Fig. 6 we have also plotted the dynamical masses and luminosities derived for other binary Cepheids. Their positions also indicate excess mixing in their main sequence progenitors, corresponding to convective overshoot mixing by about 0.25 to 0.8 pressure scale heights. While for each star the error bars are rather large, the close agreement for the different stars reduces the uncertainty considerably.

The triple star SU Cyg, studied by Evans & Bolton (1988), appears to be the exception.

As seen from Fig. 6 the final decision about the degree of excess mixing determined in this way depends also on the final luminosity calibration for Cepheids. (Only the determination of the degree of excess mixing from the comparison of luminosities for Cepheids and their evolved companions is independent of the final luminosity calibration.) The vertical arrows in Fig. 6 indicate the change in log L/L☉ corresponding to an increase in the distances by 10% as suggested by Feast & Catchpole (1997).

7. SUMMARY

7.1 The Mass of Y Carinae and the Degree of Excess Mixing in its Main Sequence Progenitor

We have determined the dynamical mass for the beat Cepheid Y Carinae A. The ratio of the orbital velocities was determined to be ~1.5 ± 0.4. This gives the inverse mass ratio for the two components. The companion, Y Car B, is a B9 V star with a mass of 2.5 ± 0.1 M☉. This leads to a mass of 3.8 ± 1.2 M☉ for the Cepheid. Using its luminosity, determined from the period–luminosity relation, or the magnitude of its main sequence companion, the M–L relation for Y Carinae, taking its dynamical mass at its face value, indicates an amount of excess mixing in the core of its main sequence progenitor, which corresponds to convective overshoot mixing by about 1 pressure scale height. The large error limits for the dynamical mass do not, however, permit a firm conclusion. The determination is based on only two spectra, one of which is extremely weak and noisy.

7.2 The Period Ratio of Y Carinae and the OPAL Opacities

As pointed out above, the period ratio for beat Cepheids depends sensitively on the opacities, in addition to its dependence on mass, luminosity and T eff. With mass and T eff now known for the beat Cepheids Y Car A we were able to test the validity of the new OPAL opacities by comparing the theoretical relation between P0 and P/P0 with the observations. For the determined dynamical mass of 3.8 solar masses we find good agreement between theoretical and observed values, thus confirming the OPAL opacities. Though the uncertainty in the dynamical mass is large, it definitely excludes the old, low beat masses.

Adopting then the model calculations incorporating the OPAL opacities we can determine the beat mass for the beat Cepheid, Y Car A, from a comparison of the theoretical and observed ratio P0/P. We find very good agreement for log L/L☉ = 3.05, T eff ~ 5960 K and M/M☉ = 3.85. A mass larger than 4 solar masses appears to be excluded because such models would yield fundamental periods that are too large as compared to the observed one, and for a given period would require too low effective temperatures.

Support for this work was provided by NASA Grant No. GO-4541.02 to E.B.V. and GO-4541.02 to K.G.C. from the
Space Telescope Science Institute, which is operated by the association of Universities for Research in Astronomy, Incorporated, under NASA Contract No. NAS5-26555. We are very much indebted to the Program Coordinator, Contact Scientists, and Schedulers at the Space Telescope Science Institute for their assistance and support in obtaining these observations. N.R.E. is grateful for grants from the Natural Sciences and Engineering Council, Canada, and from the AXAF Science Center NASA Contract No. NAS8-39073. Computer facilities were partly furnished by Dr. J. Caldwell at York University. We also wish to express our gratitude to Dr. F. Fekel for providing us with a list of stars, that show no measurable radial velocity changes, which could be used as velocity standards.

REFERENCES

Balona, L. A. 1983, Observatory, 103, 163
Feast, M. W., & Catchpole, R. M. 1997, preprint
Fekel, F. 1996, private communication