THE ASTROPHYSICAL JOURNAL, 494:768–772, 1998 February 20

CLASSICAL CEPHEID MASSES: U AQUILAE[1]

NANCY REMAGE EVANS
Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge, MA 02138; nevans@cfa.harvard.edu
ERIKA BÖHM-VITENSE
Astronomy Department, University of Washington, Seattle, WA 98195; erica@bluemoon.astro.washington.edu
KENNETH CARPENTER
Laboratory for Astronomy and Solar Physics, NASA/Goddard Space Flight Center, Code 681, Greenbelt, MD, 20771; hrscarpenter@tma1.gsfc.nasa.gov
BERNHARD BECK-WINCHATZ
Astronomy Department, University of Washington, Seattle, WA 98195; bbeck@bluemoon.astro.washington.edu
AND
RICHARD ROBINSON
Astronomy Programs, Computer Sciences Corporation, NASA/Goddard Space Flight Center, Code 681/CSC, Greenbelt, MD, 20771; hrsrobinson@tma1.gsfc.nasa.gov
Received 1997 July 21; accepted 1997 October 1

ABSTRACT

We have obtained medium-resolution spectra ($\lambda/\Delta\lambda \sim 20{,}000$) of the hot binary companion to the classical Cepheid U Aql with the Goddard High Resolution Spectrograph on the *Hubble Space Telescope* (*HST*). These have been used to determine the orbital velocity amplitude. Combining this with the orbital velocity amplitude of the Cepheid from the ground-based orbit and the mass of the companion inferred from its spectral type, we measure a mass of the Cepheid of $5.1 \pm 0.7\ M_{\odot}$. We discuss the full sample of Cepheids for which we have determined masses with *HST* (S Mus, V350 Sgr, Y Car, and U Aql) and also SU Cyg (mass from *IUE*). The *HST* masses are in agreement with the luminosities predicted by recent evolutionary tracks with moderate overshoot. This comparison, however, may be altered by reassessment of Cepheid distances based on *Hipparcos* parallaxes.

Subject headings: binaries: spectroscopic — Cepheids — stars: fundamental parameters — stars: individual (U Aquilae)

1. INTRODUCTION

Satellite ultraviolet spectroscopy has made it possible to pursue the illusive goal of observationally determining the masses of classical Cepheid variable stars. The combination of an accurate mass with accurate luminosity provided by the instability strip fiducial provides a good test of evolutionary calculations in the evolved region of the H-R diagram. The approach is to determine the orbit of the Cepheid from the ground where it completely dominates the light of the system. A fainter but hotter companion will dominate the light in the ultraviolet. The orbital velocity of the companions at orbital velocity minimum and maximum can be measured from satellite ultraviolet spectra. The orbital velocity amplitudes for the Cepheid and the companion provide the mass ratio between the two stars. Combining this with the mass of the companion inferred from the spectral type from a low-resolution ultraviolet spectrum provides the mass of the Cepheid.

As is summarized in Evans et al. (1997), the masses inferred from evolutionary calculations and those from pulsation calculations are now in reasonable agreement because of the introduction of the increased envelope opacities (Rogers & Iglesias 1992). A number of groups currently produce evolutionary calculations, among them the Geneva group (Schaller et al. 1992) and the Padua group (Bertelli et al. 1994). The treatment of convective mixing at the main-sequence core boundary is a particularly important parameter in determining the luminosity a star with a given mass will have in the later blue loop (Cepheid) phase. Both these groups use a moderate amount of overshoot (the ratio of the overshoot distance to pressure scale height of 0.2), as well as the new opacities. Currently work is in progress by these groups to extend the calculations to include rotation (Geneva) and a new treatment of convective mixing (Padua).

This study discusses the final system in a series of five that we have studied with the Goddard High Resolution Spectrograph (GHRS) on the *Hubble Space Telescope* (*HST*). So far masses for S Mus (Böhm-Vitense et al. 1997c), V350 Sgr (Evans et al. 1997), Y Car (Böhm-Vitense et al. 1997b), and V636 Sco (Böhm-Vitense et al. 1997a) have been determined in this manner.

The approach was developed with *IUE* spectra (Böhm-Vitense et al 1990; Böhm-Vitense 1986; Evans & Bolton 1990). The present work improves on the *IUE* results because of the higher spectral resolution, the greater sensitivity, and the higher absolute wavelength accuracy. This last feature in particular allows us to use shorter wavelength spectra where only the companion is seen in the spectrum rather than the composite spectrum at longer ultraviolet wavelengths. Only the Cepheid triple system SU Cyg (Evans & Bolton 1990) is unsuitable for improvement with GHRS because many observations are required that need to be precisely scheduled, since the companion is itself a binary. However, because the dominant hot star in the system has strong sharp lines, its velocity has been mea-

[1] Based on observations made with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NASA-26555.

TABLE 1
GHRS SPECTRA OF U AQL

Visit	JD $-2{,}400{,}000$	Exposure Time (minutes)	ϕ_{orb}	V_{orb} ($km\ s^{-1}$) Cepheid
V1......	49,447.16	72	0.605	6.0
V2......	50,238.10	148	0.032	−7.1

sured quite successfully in *IUE* spectra. (Further work is in progress on this system based on additional *IUE* spectra.)

The purpose of this study is to measure the orbital velocity amplitude of the hot companion of the Cepheid U Aql in the ultraviolet. Combining this amplitude with the orbital velocity amplitude of the Cepheid from the ground-based orbit (Welch et al. 1987) produces the mass ratio of the two stars. In addition to this mass ratio, the mass of the companion is needed. A spectral type (B9.8 V) has been determined by Evans (1992a) from *IUE* low-resolution spectra. From these data, we will determine the mass of the Cepheid.

In § 2 below we discuss the *HST* observations, in § 3 the velocities, and in § 4 the mass and properties of the system, as well as the implications from the series of masses that we have determined.

2. OBSERVATIONS

Observations of U Aql B were made with the GHRS on the *HST* on 1994 April 4 and 1996 June 3 (Table 1). Exposure times of 72 and 148 minutes, respectively, were obtained. The medium-resolution grating G200M was used because of the faintness of the target, providing a resolution of $R = \lambda/\Delta\lambda \sim 20{,}000$ (Heap et al. 1995). The wavelength range 1840–1880 Å was used. The observing procedure is described in Evans et al. (1997), in particular the steps taken to ensure maximum wavelength accuracy. These included using the Small Science Aperture (0″.22 on a side), breaking the exposure into 5 minute segments to avoid smearing because of thermal and magnetic variations, and wavelength calibration exposures at the beginning and end of each orbit. These calibration spectra were used to derive a small wavelength correction by interpolation before adding all the segments within an orbit. Finally the spectra from all the orbits were added. For the second observation, a model of the Earth's magnetic field variations (often called GIMP) was used to co-add the segments; however, the linear interpolation used to create the spectrum from the first visit should be equally accurate. The spectral reductions were done with the CALHRS routine, including current calibration data.

Because of the observing strategy, the wavelength scale should be accurate to 2.7 km s^{-1}, as estimated by Heap et al. (1995). The dominant source of error is the centering of the Small Science Aperture.

The spectra from the two observations are shown in Figure 1.

3. VELOCITIES

As in the case of V350 Sgr, comparison of the spectra in Figure 1 with either of the standard star spectra (α Lyr or HD 72660) shows that the relatively shallow features in the U Aql spectra are different from the deeper features of the standards. The standard spectra that convolved with a rotational broadening function of 100 or 150 km s^{-1} are a much better match to the U Aql spectra.

The U Aql spectra can be directly cross-correlated, resulting in a cross-correlation function such as the one shown in Figure 2. As with V350 Sgr, the velocity depends slightly on the smoothing of the data. However, nine com-

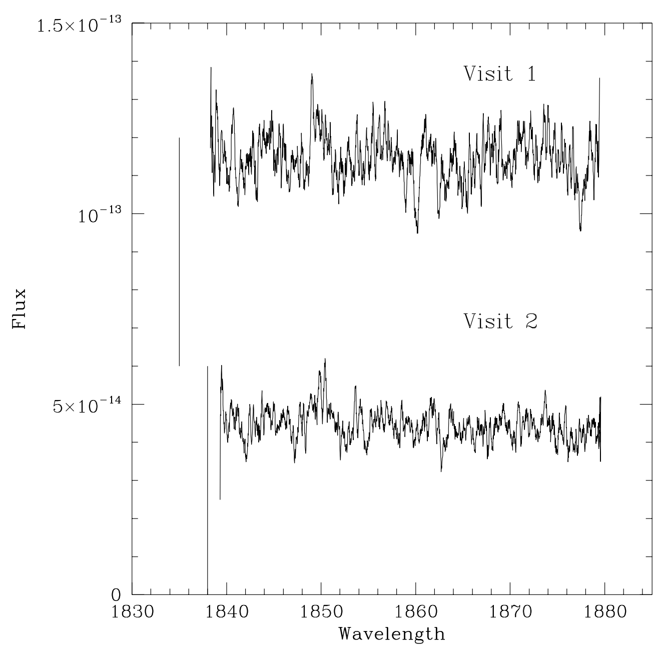

FIG. 1.—GHRS G200M spectra of the two spectra of U Aql. In order to separate the two spectra, 6×10^{-14} ergs cm^{-2} s^{-1} $Å^{-1}$ has been added to the spectrum from the first visit. The vertical lines on the far left indicate the continuum and zero level of each of the spectra. Both spectra have been smoothed with a 10 point boxcar. In all figures, wavelength is in Å and flux is in ergs cm^{-2} s^{-1} $Å^{-1}$.

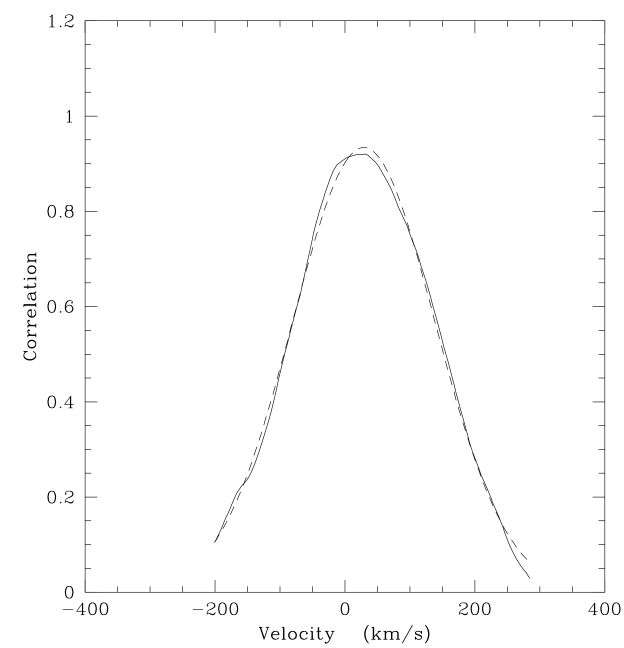

FIG. 2.—Cross-correlation function for the two U Aql B spectra. The solid line is the observed correlation function; the dashed line is a Gaussian fit to the correlation function to determine the velocity. The Gaussian width of 103 km s^{-1} confirms that the U Aql B spectra are rotationally broadened. A 30 point boxcar smoothing has been used on the spectra, which, however, only increases the broadening by about 10%.

binations of a 5 point boxcar smoothing followed by a smoothing ranging from 5 to 25 points led to velocities between -28.3 and -30.2 km s^{-1} for the velocity difference between the first and second spectra. The velocity difference we derive is thus -29.1 km s^{-1}.

From two spectra we cannot directly derive an uncertainty in the velocity difference. The aperture centering, however, is the dominant error, since we have wavelength calibrations. We adopt the uncertainty estimate from Heap et al. (1995) of 2.7 km s^{-1} or 3.8 km s^{-1} for the velocity difference.

We have estimated the rotation velocity $v \sin i$ from the gakf-width at half-maximum (HWHM/$2^{1/2}$) (Fig. 2) to be 90 km s^{-1}.

As in the case of V350 Sgr (Evans et al. 1997), we have investigated the possible effect of two interstellar lines (1854.7 and 1862.8 Å) on the velocities. Visual inspection of the spectra does not indicate features stronger than the noise. Experiments removing the wavelength region of one or both of these lines from the correlation resulted in smaller velocity differences than those obtained from the original spectra. This is the opposite of what would be expected if the velocity differences were influenced by the interstellar lines, which would tend to pull both velocities toward zero. We conclude that interstellar lines do not affect our velocities.

4. DISCUSSION

The orbital velocities of the Cepheid at the time of the GHRS observations are listed in Table 1, as computed from the orbit of Welch et al. (1987). The orbital velocity difference at these phases is 13.1 km s^{-1}. The standard deviation in the orbital velocity amplitude is 0.22 km s^{-1}. The mass ratio thus becomes $M_{\rm Cep}/M_{\rm Comp} = 2.2 \pm 0.3$. Using the mass data from Andersen (1991), the mass of the companion U Aql B with a spectral type B9.8 V (Evans 1992a) is 2.3 ± 0.1. The small error results from the high precision with which the spectral type can be derived from *IUE* spectra, and also takes into account that U Aql B must be close to the zero-age main sequence because of the young age of the Cepheid primary (Evans & Sugars 1997). The resulting mass of the Cepheid is $5.1 \pm 0.7\ M_\odot$.

Before discussing this mass in relation to the other masses we have determined, we will mention two factors related to the interpretation of the mass. First, a high rotation velocity of the companion will make it cooler; hence, we will infer too small a mass. As discussed by Evans et al. (1997), although rotation does broaden the lines of the companion perceptibly, the observed rotation velocity is only a small fraction of breakup velocity. Most of the gravity darkening only occurs for velocities larger than 90% of breakup velocity. This means that the effect on the inferred mass of the companion is negligible unless the inclination is very small.

Cepheid masses are particularly useful because they are linked with a very accurate luminosity. In the case of U Aql, we have been able to determine the luminosity of the Cepheid directly from the luminosity of the hot companion (Evans 1992a). For U Aql, the luminosity derived from the companion is 0.52 mag fainter than that inferred from the Feast & Walker (1987) period-luminosity-color (*PLC*) relation. Our interpretation continues to be that this is just observational error. (The standard deviation for a single absolute magnitude determined from hot companions is 0.33 mag.)

The Cepheids with masses determined in this paper as well as from previous papers (U Aql, S Mus, V350 Sgr, Y Car, and SU Cyg) are shown in Figure 3. We have also attempted to determine a mass for V636 Sco (Böhm-Vitense et al. 1997a). However, it appears to be a triple system, so a mass cannot be determined from the existing data, and it has been omitted from the discussion here. The Cepheid luminosities are computed from the *PLC* relation of Feast & Walker (1987). Temperatures are derived from the mean colors corrected for the companions (Evans 1995) using the Kraft color-temperature relation as discussed by Evans & Teays (1996). Feast & Catchpole (1997) advocate a new period-luminosity (*PL*) relation based on *Hipparcos* parallaxes. We have compared the proposed relation with the *PL* relation given by Feast & Walker based on the same calibrators used in the *PLC* relation above. For a 10 day Cepheid, the luminosity increase is only 0.11 mag or 0.04 in log *L*. Alternatively, Feast & Whitelock (1997) have derived a *PLC* relation based on *Hipparcos* data. That relation results in a mean absolute magnitude increase of only 0.05 mag for the stars in Figure 3 as compared with the the Feast & Walker *PLC* relation. None of these small luminosity increases have been included in Figure 3. For comparison, the evolutionary tracks computed by the Padua group (Bertelli et al. 1994) are shown. Unfortunately, the blue loops of the 4, 5, and 6 $M_\odot$ stars do not extend to temperatures as hot as the location of the Cepheids.

Because Cepheids for which masses have been observationally measured are an important group, we present them in the context of other Cepheids in Figure 4. The M_V were taken from two sources of observationally determined luminosities, the Feast & Walker (1987) determinations for stars in clusters (omitting those in associations) and the determinations from binary companions (Evans 1991, 1992a, 1992b, 1992c). For the binary stars, the colors

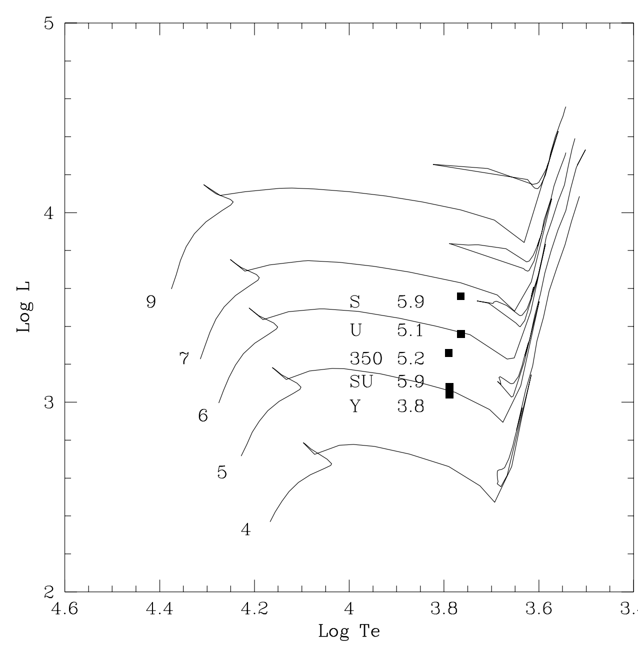

FIG. 3.—Cepheids for which masses have been determined. Just to the left of each Cepheid, the measured mass in $M_\odot$ is listed and the identity of the star is given: S for S Mus, U for U Aql, 350 for V350 Sgr, Y for Y Car, and SU for SU Cyg. For comparison the evolutionary tracks computed by Bertelli et al. (1994) are shown. The mass for each track is shown near the main sequence (in $M_\odot$). Temperature is in K; luminosity is in $L_\odot$.

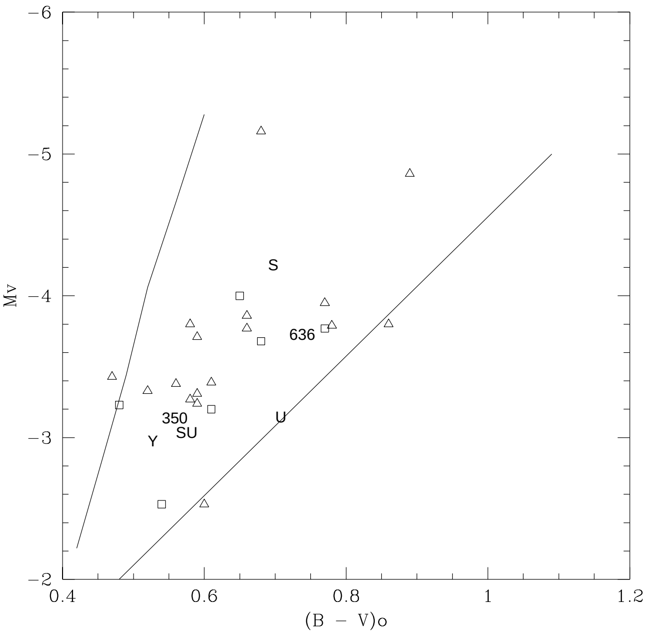

FIG. 4.—H-R diagram for Cepheids with independently determined luminosities. The Cepheids for which we have determined masses are shown by the same individual symbols as in Fig. 3 (and also 636 for V636 Sco). SU Cyg has been displaced slightly downward for clarity. The triangles are for luminosities for cluster Cepheids as given by Feast & Walker (1987); the squares are for luminosities from binary companions. The lines are the approximate boundaries of the instability strip as given by Fernie (1990) for field stars with absolute magnitudes inferred from the *PLC*. Both absolute magnitude and color are in magnitudes.

$\langle B_0 \rangle - \langle V_0 \rangle$have been corrected for the effects of the companions. Luminosities have been determined from binary companions for the stars with masses in Figure 4, except for S Mus and SU Cyg. For these stars, direct determination of the Cepheid luminosity could be complicated by evolution in the companion and in a third star, respectively. In these cases, M_V in Figure 4 is from the Feast & Walker *PLC*, and corrected colors are from Evans (1995). We have also included Polaris in the list of calibrators, using the *Hipparcos* parallax given by Feast & Catchpole (1997). This is the only parallax in the list large enough to be individually useful.

While Feast & Catchpole (1997) conclude that the distance scale of Cepheids should be increased, other relevant results from the *Hipparcos* mission are still being assessed. In particular, new distances have been obtained for the Pleiades and other clusters. Madore & Freedman (1997) point out that *Hipparcos* parallaxes indicate a decrease in the distance to the Pleiades (though not all clusters show decreases in distance).

Fernie (1990) investigated the location of the instability strip as outlined by 100 Cepheids with luminosities inferred from the Feast & Walker *PLC* relation. For comparison in Figure 4, we show the blue edge found to contain that large sample (derived from theoretical tracks) and the red edge from the observed sample.

Figure 4 shows that the sample of Cepheids for which we have been able to determine masses has no particular selection effects in terms of location within the strip. They are generally well inside the strip. U Aql is near the edge; however, the brighter luminosity from the *PLC* relation (see above) places it well within the strip. There is no reason to think there is anything unusual about the Cepheids in our mass sample.

Figure 5 summarizes the current information about Cepheid masses. For comparison, the luminosities of the tips of the blue loops are shown from the calculations of several groups. The most recent tracks from both the Geneva group (Schaller et al. 1992) and the Padua group (Bertelli et al. 1994) include the same (moderate) main-sequence core convective overshoot, an overshoot distance of 0.2 pressure scale heights (Schaller et al. 1992). The blue loop tips from the current Geneva/Padua tracks fall near the observed masses. For comparison, the tracks of Becker (1981) and older Padua tracks which have no convective overshoot and full convective overshoot, respectively (Bertelli et al. 1986), are shown. The location of the tips does depend somewhat on the opacities, so new tracks can only be compared approximately with the old tracks. For otherwise equal stellar parameters, the new opacity models appear to have slightly lower luminosities than the lower opacity models (see Bressan et al. 1993). As mentioned in connection with Figure 3, comparison with the blue loop tips is only an approximate comparison due to the stunted loops at lower masses. While we have used the luminosity of the bluest extent for the 5 $M_{\odot}$ track, it is quite possible that if the track were to extend further to the blue, it would rise to a higher luminosity.

Figure 5 shows that all the mass determinations fall slightly above the moderate overshoot tracks, indicating somewhat more mixing than assumed for those tracks, though the error bars reach the moderate mixing tracks as well as the strong mixing tracks. One way to summarize the masses that have been determined is to create for each an

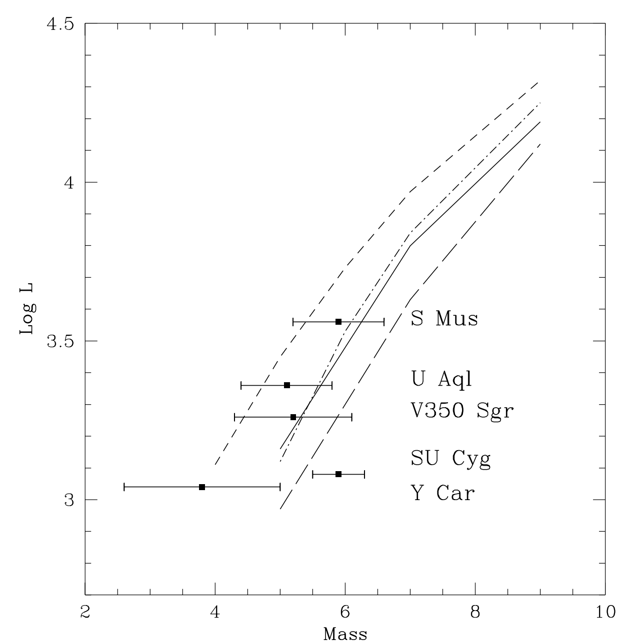

FIG. 5.—Cepheid masses summarized. The masses of the Cepheids (*named at the right*) are shown in comparison with evolutionary predictions for the luminosity of the blue loop tips. The recent Geneva tracks are the solid line; recent Padua tracks are shown by the dot-dashed line. These tracks use the same (moderate) convective overshoot. For comparison, Becker tracks (no overshoot) are shown by the long-dashed line, and older Padua tracks with full overshoot by the short-dashed line. See text for discussion. Error bars are 1 σ; luminosity is in $L_{\odot}$; mass is in $M_{\odot}$.

TABLE 2

CEPHEID MASSES

Star (1)	Mass ($M_\odot$) (2)	S Mus-Geneva ($M_\odot$) (3)	S Mus-Padua ($M_\odot$) (4)	Instrument (5)
S Mus	5.9 ± 0.7	5.9 ± 0.7	5.9 ± 0.7	*HST*
V350 Sgr	5.2 ± 0.9	6.1 ± 0.9	6.0 ± 0.9	*HST*
Y Car	3.8 ± 1.2	5.4 ± 1.2	5.2 ± 1.2	*HST*
U Aql	5.1 ± 0.7	5.7 ± 0.7	5.7 ± 0.7	*HST*
SU Cyg	5.9 ± 0.4	7.4 ± 0.7	7.2 ± 0.7	*IUE*
Mean without SU Cyg	...	5.8 ± 0.2	5.8 ± 0.3	...
Mean with SU Cyg	...	6.6 ± 0.9	6.5 ± 0.8	...
Predicted S Mus	...	6.3	6.1	...

"equivalent S Mus mass"—that is, to use a slope $d \log L/dM$ to calculate for each Cepheid the mass it would have if it had the luminosity of S Mus. We have used the slopes determined from 5 and 7 $M_\odot$ in the Geneva tracks (Schaller et al. 1992) and the 5 and 6 $M_\odot$ in the Padua tracks (Bertelli et al. 1994). As noted above, it is possible that the stunted blue loop tracks underestimate the luminosities for the lowest mass stars. The result would be that we would underestimate the "equivalent S Mus mass."

Table 2 lists the results. Column (2) is the observed mass; column (3) is the "equivalent S Mus mass" using the slope from the Geneva tracks (Schaller et al. 1992); column (4) is the "equivalent S Mus mass" using the slope from the Padua tracks (Bertelli et al. 1994). At the bottom of the table is listed the mean "equivalent S Mus mass." It is clear that the difference in using the two slopes is negligible. The "predicted mass of S Mus" in the bottom row of Table 2 is the mass from each set of tracks corresponding to the luminosity of S Mus. The "equivalent S Mus mass" is slightly smaller than that predicted by either set of tracks if SU Cyg is excluded from the mean. It is slightly larger if SU Cyg is included.

With the caveats above on the comparisons with evolutionary tracks, the equivalent mass of S Mus corresponds to an overshoot distance $\simeq 0.3$ times the pressure scale height if SU Cyg is excluded. If SU Cyg is included, the overshoot distance is $\simeq 0.1$ times the pressure scale height. (As stated by Bressan et al. 1993, their moderate overshoot parameter $\Lambda = 0.5$ corresponds to the overshoot distance, 0.2 times the pressure scale height, used by the Geneva group. The full overshoot of the Padua group is twice that size.)

We stress again that while the masses have now been measured, statements about overshoot depend also on the calibrated luminosities of the Cepheids. The *Hipparcos* parallaxes are providing material for a reassessment of these luminosities.

To summarize:

1. We have measured the orbital velocity amplitude of the hot binary companion to U Aql using GHRS medium resolution spectra.
2. Combining this with the orbital velocity amplitude of the Cepheid from the ground-based orbit and the mass of the companion inferred from its spectral type, we measure a mass of the Cepheid of $5.1 \pm 0.7\ M_\odot$.
3. We have made approximate comparisons with recent evolutionary tracks from Schaller et al. (1992) and Bertelli et al. (1994) for the whole sample of Cepheids for which the masses have been determined. The comparison is hindered because theoretical blue loops for lower mass stars do not enter the instability strip.
4. The masses are in approximate agreement with the recent tracks which use an overshoot distance of 0.2 pressure scale heights. A slightly larger value ($\simeq 0.3$) results if SU Cyg is omitted; a slightly smaller value ($\simeq 0.1$) if SU Cyg is included. The value inferred for overshoot, however, depends both on the masses and on the luminosities.

We are happy to thank the staff at the Space Telescope Science Institute for their assistance in obtaining these data. Conversations with D. Sasselov improved the content to the paper, as did comments from the referee, M. Feast. Financial upport was provided by NASA grant GO-4541-01 to E. B.-V. and GO-4541.02 to K. C., a grant from the Natural Sciences and Engineering Council, Canada, to N. R. E., and from the *AXAF* Science Center NASA contract NAS 8-39073.

REFERENCES

Andersen, J. 1991, A&A Rev., 3, 91
Becker, S. A. 1981, ApJS, 45, 475
Bertelli, G., Bressan, A., Chiosi, C., & Angerer, K. 1986, A&AS, 66, 191
Bertelli, G., Bressan, A., Chiosi, C., Fagatto, F., & Nasi, E. 1994, A&AS, 106, 275
Böhm-Vitense, E. 1986, ApJ, 303, 262
Böhm-Vitense, E., Clark, M., Cottrell, P. L., & Wallerstein, G. 1990, AJ, 99, 353
Böhm-Vitense, E., Evans, N. R., Carpenter, K., Beck-Winchatz, B., Albrow, M., Cottrell, P., & Robinson, R. 1997a, preprint
Böhm-Vitense, E., Evans, N. R., Carpenter, K., Beck-Winchatz, B., Morgan, S., & Robinson, R. 1997b, AJ, submitted
Böhm-Vitense, E., Evans, N. R., Carpenter, K., Beck-Winchatz, B., & Robinson, R. 1997c, ApJ, 477, 916
Bressan, A., Fagotto, F., Bertelli, G., & Chiosi, C., 1993, A&AS, 100, 647
Evans, N. R. 1991, ApJ, 372, 597
———. 1992a, ApJ, 389, 657
———. 1992b, ApJ, 385, 680
Evans, N. R. 1992c, AJ, 104, 216
———. 1995, ApJ, 445, 393
Evans, N. R., Böhm-Vitense, E., Carpenter, K., Beck-Winchatz, B., & Robinson, R. 1997, PASP, in press
Evans, N. R., & Bolton, C. T. 1990, ApJ, 356, 630
Evans, N. R., & Sugars, B. J. A. 1997, AJ, 113, 972
Evans, N. R., & Teays, T. J. 1996, AJ, 112, 761
Feast, M. W., & Catchpole, R. M. 1997, MNRAS, 286, L1
Feast, M. W., & Walker, A. R. 1987, ARA&A, 25, 345
Feast, M. W., & Whitelock, P. 1997, MNRAS, in press
Fernie, J. D. 1990, ApJ, 354, 295
Heap, S. R., et al., 1995, PASP, 107, 871
Madore, B. F., & Freedman, W. L. 1997, ApJ, 492, 110
Rogers, F. J., & Iglesias, C. A. 1992, ApJS, 79, 507
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
Welch, D. L., Evans, N. R., Lyons, R. W., Harris, H. C., Barnes, T. G., III, Slovak, M. H., & Moffett, T. J. 1987, PASP, 99, 610