

BINARY CEPHEIDS: SEPARATIONS AND MASS RATIOS IN $5 M_{\odot}$ BINARIES*

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ABSTRACT

Deriving the distribution of binary parameters for a particular class of stars over the full range of orbital separations usually requires the combination of results from many different observing techniques (radial velocities, interferometry, astrometry, photometry, direct imaging), each with selection biases. However, Cepheids—cool, evolved stars of $\sim 5 M_{\odot}$ —are a special case because ultraviolet (UV) spectra will immediately reveal any companion star hotter than early type A, regardless of the orbital separation. We have used *International Ultraviolet Explorer* UV spectra of a complete sample of all 76 Cepheids brighter than $V = 8$ to create a list of all 18 Cepheids with companions more massive than $2.0 M_{\odot}$. Orbital periods of many of these binaries are available from radial-velocity studies, or can be estimated for longer-period systems from detected velocity variability. In an imaging survey with the *Hubble Space Telescope* Wide Field Camera 3, we resolved three of the companions (those of η Aql, S Nor, and V659 Cen), allowing us to make estimates of the periods out to the long-period end of the distribution. Combining these separations with orbital data in the literature, we derive an unbiased distribution of binary separations, orbital periods, and mass ratios. The distribution of orbital periods shows that the $5 M_{\odot}$ binaries have systematically shorter periods than do $1 M_{\odot}$ stars. Our data also suggest that the distribution of mass ratios depends on both binary separation and system multiplicity. The distribution of mass ratios as a function of orbital separation, however, does not depend on whether a system is a binary or a triple.

Key words: binaries: general – stars: massive – stars: variables: Cepheids

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1. INTRODUCTION

Binary-star studies are valuable for what they provide directly (e.g., stellar masses), as well as for the information they provide about the configurations resulting from star formation processes. This topic was particularly well developed in a classical series of studies by Abt and collaborators. For instance, Abt et al. (1990) discussed this question for late B stars.

For several decades, binary-star studies have been the beneficiary of developments in observational techniques, particularly those providing high spatial resolution and access to new wavelength regions. A clear demonstration of progress in this area was the discussion by Duquennoy & Mayor (1991) of the binary properties of solar-mass stars. They combined extensive CORAVEL radial-velocity (RV) observations with results from visual binaries and common-proper-motion stars to explore distributions of mass ratios and eccentricities at all separations. Recently this work has been updated by Raghavan et al. (2010) to include new advances in high-resolution techniques (long-baseline interferometry and speckle interferometry). Stars more massive than solar type are more difficult to study because they are rarer, and hence more distant, and also because they have broad spectral lines that limit the accuracy of RVs. However, new observational techniques have likewise greatly

enhanced the knowledge of their properties (e.g., Kobulnicky & Fryer 2007; Kouwenhoven et al. 2007; Mason et al. 2009; Sana & Evans 2011). Sana & Evans, for instance, find a fairly constant fraction (44%) of spectroscopic binaries among OB stars in several nearby open clusters. Systems with small mass ratios (i.e., low secondary masses) are the most difficult to identify. Evans et al. (2011a) have used a different approach to determine the fraction of B stars with low-mass companions. Since late B stars produce X-rays very rarely, the fraction of late B stars in the young cluster Tr 16 (associated with η Car) that were detected in X-rays provides the fraction (32%–39%) that have young low-mass companions.

Comparing the observed properties of binary and multiple systems with star formation calculations is a test of the model predictions. An obvious first step of this approach is a comparison of the properties of binary systems containing high- and low-mass primary stars, but our knowledge of binaries among intermediate- and high-mass stars is still not as extensive as it is for solar-mass stars.

This paper is the first in a series aimed at determining the properties of binary systems containing Cepheid variables. Cepheids are stars of intermediate masses, ranging from about 4 to 9 $M_{\odot}$; in this paper we will use $5 M_{\odot}$ as the typical Cepheid mass. Cepheids are particularly useful for determining binary properties for several reasons. They have narrow spectral lines, providing accurate RVs from optical spectroscopy. If a Cepheid has a fairly high-mass companion, the companion will dominate the light of the system in the ultraviolet (UV), thus immediately demonstrating that the system is a binary. This further makes it possible to determine masses by measuring the orbital velocity

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amplitude of the companion in the UV, for example by using *Hubble Space Telescope* (*HST*) spectra (e.g., Evans et al. 2011b). The combination of the optical and UV RV curves provides the mass ratio, and, if the mass of the hot companion is inferred from its spectral type, the actual mass of the Cepheid as well. Such studies provide direct evidence about the distribution of mass ratios in binaries containing Cepheids (e.g., Evans 1995). They also provide information about the fraction of triple systems (Evans et al. 2005) because the companions can be directly studied in the UV. A number of Cepheid-containing triple systems have been identified through RV variability of the companions (or inferred from the orbital mass functions). As compared with a sample of single-lined spectroscopic binaries, the ability to directly observe the companions provides a much higher detection rate of triples.

This paper focuses on a complete sample of B- and early A-type companions of Cepheid variables, which was obtained through a survey with the *International Ultraviolet Explorer* (*IUE*) satellite, as described in Section 2. This approach has the strength that the survey is sensitive to binary companions at all possible separations. By contrast, RV studies only find the close systems. Conversely, the limitation of this approach is that it does not detect low-mass companions.

The properties of the massive companion set include a few results from our recent *HST* snapshot imaging survey of Cepheids with the Wide Field Camera 3 (WFC3)—to be described in more detail in a subsequent paper—as well as orbital information on our sample from the literature. In the following sections we discuss the construction of the sample, the derivation of the orbital separations and mass ratios, their distribution functions, and some implications of our results.

2. THE SAMPLE

In order to have a well-defined sample, we start with a spectroscopic survey of all 76 Galactic Cepheids brighter than visual magnitude 8, which was carried out with the *IUE* satellite by one of us (Evans 1992a). These spectra, obtained with *IUE*'s LWP and LWR cameras, covered the near-ultraviolet (NUV) wavelength range 2000 to 3200 Å. From this study we selected the Cepheids for which *IUE* revealed a companion of spectral type A2 V or earlier, corresponding to companion masses greater than about $2 M_{\odot}$ (e.g., Harmanec 1988). These are highly probable physical companions because the rarity of A- and B-type stars in the field makes it very unlikely that such a star would be within the *IUE* aperture by chance.

The sensitivity of this *IUE* survey to hot companions varies somewhat from star to star because of differences in the intrinsic luminosity of the Cepheids, differences in the pulsation phases (hence magnitude and color) at the time of the observation, and different exposure times. One product of the survey was a list of the spectral types of the brightest companions of each Cepheid that would *not* have been detected (Evans 1992a, Table 1C). These limits were generally mid-A spectral types, but they were early A for some, and late B for four stars.

Of the complete sample of 76 Cepheids observed in the NUV with *IUE*, 15 of them had detected A- or B-type companions (Evans 1992a, Table 3A). To this list we have added three more Cepheids: (1) V636 Sco and T Vul, because hot companions of both stars were detected with the *IUE* far-ultraviolet (FUV) spectrograph and SWP camera (Evans 1992b, Table 3B; they were not evident on the 2000 to 3200 Å exposures presumably because of the phase of the Cepheid) and (2) δ Cep itself, because trigonometric parallaxes obtained with the fine guidance sensor

(FGS) on *HST* showed that the Cepheid and its 40'' B-type companion HD 213307 are at the same distance (Benedict et al. 2002). Our list of the 18 Cepheids with companions of $2 M_{\odot}$ or more is given in Table 1.

For each Cepheid that had a detected hot companion, spectral types are available from *IUE* observations in the FUV spectral range (1150–1950 Å). FUV spectra of late B and early A stars are particularly sensitive to temperature changes, and such companions completely dominate the spectra, so the spectral types are tightly constrained. The spectral classifications were derived by comparison with *IUE* SWP spectra of MK standard stars. Because the spectral energy distribution is so temperature-sensitive, many of the companions were found to have spectral types between those of the MK standards, resulting in fractional spectral types such as B9.8 V. Table 1 lists the spectral types for the companions and the references from which they were taken (Columns 2 and 3). Many of the cited sources provide plots directly comparing the companion spectra with those of MK standards.

Masses of the companions were derived from their spectral types, and are given in Column 4 of Table 1. For the late B and early A companions, the large luminosity difference between the Cepheid and the companion means that the companion can be assumed to lie on the zero-age main sequence (ZAMS). For the ZAMS, we use the Harmanec (1988) calibration of masses versus spectral types. The masses for these stars in Table 1 are mostly taken from Evans (1995), but our new values for η Aql, SU Cas, S Nor, T Vul, and the systems discussed below.

Table 1 also contains three hotter companions, some of which may have evolved beyond the ZAMS; these objects were discussed by Evans (1994). Masses for AX Cir, BP Cir (overtone mode), and V659 Cen are from Figure 7 in that paper, and are based on the Geneva evolutionary tracks, which include mild core convective overshoot.

A few companion masses in Table 1 require further discussion.

1. δ Cep. The spectral type and mass for the companion, HD 213307, are taken from Benedict et al. (2002).
2. *S Mus*. The companion spectral type was derived from *FUSE* spectra (Evans et al. 2006b), from which the mass was derived as discussed in that paper.
3. *AW Per*. The Cepheid and its companion have been rediscussed by Massa & Evans (2008), who derived a temperature for the hottest companion of $T_{\text{eff}} = 15735 \pm 248$ K. This effective temperature is used with the Harmanec relation to derive the mass and spectral type given in Table 1. Massa & Evans confirm, however, that the secondary is itself a binary based on the mass function of the spectroscopic orbit.
4. *T Mon*. From *HST* high-resolution UV spectra, Evans et al. (1999) found that the companion is a magnetic chemically peculiar Ap star, very similar to α^2 CVn, and also a binary. The companion mass is taken from that paper.

Table 1 contains a sample of intermediate-mass companions of $\sim 5 M_{\odot}$ stars with uniquely complete information over the full range of separations. However, there are some further points that need to be addressed. As is typical of massive stars, there is a high fraction of triple systems in this list of binaries (Evans et al. 2005). The spectral types and masses in Table 1 pertain to the hottest companion star in the system, but there may be additional system members. Two examples are as follows. (1) W Sgr is a spectroscopic binary with a period of 1780 days, and *IUE*

Table 1
Cepheids Brighter than $\langle V \rangle = 8$ with Companions $M > 2 M_{\odot}$

Star	Spect. Type	Ref.	M_2 ($M_{\odot}$)	Binary Type ^a	P_{orb} (days)	$\log P_{\text{orb}}$ (days)	$\log a$ (AU)	q (M_2/M_1)	Triple?	Ref.
η Aql	B9.8 V	3	2.3	r	...	5.5	2.3	0.40	t	12
U Aql	B9.8 V	1	2.3	o	1856	3.27	0.77	0.40	t	11
RX Cam	A0 V	1	2.2	o	1113	3.05	0.62	0.38		
SU Cas	B9.5 V	3	2.4	...	...	5.1	2.0	0.57		
V659 Cen	B6.0	4	4.4	r	...	6.1	2.7	0.85		
δ Cep	B7-8	10	4	r	...	8.1	4.0	0.77	t	10
AX Cir	B6.0	4	5.0	o	6532	3.82	1.17	0.96		
BP Cir	B6.0	4	4.7	om	...	3.9	1.2	1.05		
SU Cyg	B8.0 V	1	3.2	o	549	2.74	0.42	0.68	t	11
V1334 Cyg	B7.0 V	1	4.0	o	1938	3.29	0.80	0.82		
T Mon	A0p	8	3.0	om	...	4.7	1.8	0.33	t	8
S Mus	B3 V	7	5.3	o	505	2.70	0.45	0.85		
S Nor	B9.5 V	2	2.4	r	...	6.5	2.9	0.38		
AW Per	B6:	6	4.0	o	13100	4.12	1.36	0.74	t	11
W Sgr	A0 V	1	2.2	r	...	4.8	1.8	0.38	t	11
V350 Sgr	B9.0 V	5	2.5	o	1473	3.17	0.70	0.49		
V636 Sco	B9.5 V	1	2.4	o	1318	3.12	0.67	0.43	t	11
T Vul	A0.8 V	9	2.1	...	...	4.9	1.8	0.43		

Notes.

^a Binary types: o = spectroscopic orbit with known period, given in Column 6; om = spectroscopic orbital motion detected, estimated log period given in Column 7; r = resolved binary, estimated log period given in Column 7.

References. (1) Evans 1995; (2) Evans 1992c; (3) Evans 1991; (4) Evans 1994; (5) Evans & Sugars 1997; (6) Massa & Evans 2008; (7) Evans et al. 2006b; (8) Evans et al. 1999; (9) Evans 1992b; (10) Benedict et al. 2002; (11) Evans et al. 2005; (12) This paper.

revealed an A0 V companion. However, spatially resolved UV spectra obtained by Evans et al. (2009) with the *HST* Space Telescope Imaging Spectrograph (STIS) showed that the A0 V star is resolved from the Cepheid at a separation of $0''.1645$, based on an analysis of STIS spectra taken at several telescope roll angles. Thus the A0 V star is not the secondary component in the 1780 day binary, and the system is a triple. (2) V1334 Cyg is a single-lined spectroscopic binary with an orbital period of 1938 days (Evans 2000), and a B7 V companion detected by *IUE*. V1334 Cyg is cataloged as the resolved double star ADS 14859 with several reports of a companion being seen by visual observers at separations of $0''.1$ – $0''.2$; if this is so, V1334 Cyg would also be a triple system. However, neither *HST* FGS interferometry nor Faint Object Camera imaging (1998–2000) were able to resolve the visual companion. There were also no convincing detections of a companion in speckle-interferometry measurements between 1976 and 2005 (Evans et al. 2006a). Very recently, however, Gallenne et al. (2013), using the CHARA array, reported that they resolved a very close companion in observations made at two epochs in 2012. The measured separations were $0''.00891$ and $0''.00836$. These observations indicate that the B star seen by *IUE* is the 1938 day companion, but this leaves the occasional reports of a more distant visually resolved companion unexplained.

3. ORBITAL SEPARATIONS

Having assembled the complete sample of 18 Cepheids brighter than $\langle V \rangle = 8$ that have binary companions more massive than $2 M_{\odot}$, we will now investigate the orbital separations in these systems. In Column 5 of Table 1, we indicate whether the systems have a spectroscopic RV orbit with a known period (o), have been spatially resolved (r), or have an unknown orbital period but detected orbital motion (om).

3.1. Cepheids with Known Spectroscopic Orbits

Of the 18 systems listed in Table 1, 9 have known orbital periods based on RV studies. For these binaries, the orbital periods are listed in Column 6 of Table 1, and are taken from Evans et al. (2005) or Evans et al. (2011b). The logarithms of the orbital periods are given in Column 7, and the logarithms of the orbital separations in Column 8. These objects tend, of course, to be the more compact binary systems.

3.2. Cepheids in Resolved Binaries

3.2.1. *HST* WFC3 Imaging

We have recently completed a snapshot imaging survey of 69 nearby Cepheids with the *HST* WFC3 camera (program ID number GO-12215). Full details of the survey, in particular, point-spread function (PSF) subtraction to search for resolved low-mass companions of the Cepheids, will be presented in a later paper. However, some of the results are relevant to the present study of more massive Cepheid companions.

The WFC3 images were obtained in the medium-width F621M and F845M filters, hereafter referred to as “V” and “I.” All 18 stars listed in Table 1 were imaged in the course of the snapshot survey. For three of the targets— η Aql, V659 Cen, and S Nor—the intermediate-mass companion stars were resolved. Figure 1 depicts the V-band images of these three systems, and Table 2 gives details of the observations and measurements. The companions are plainly visible although the PSF is complicated and even these relatively bright companions are significantly fainter than the Cepheid. We did not attempt to measure the brightnesses of these companions in these images since the *IUE* spectra provide information about the temperature and brightness of the companions. However, we have measured the separation from the Cepheid directly on the I-band images, which is listed in Table 2. These are, of

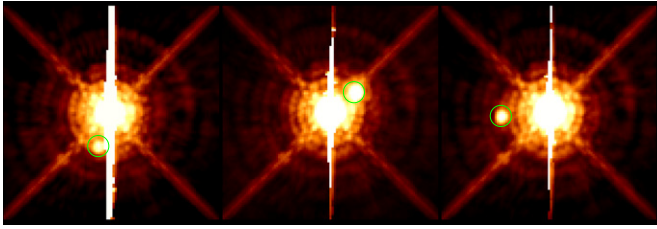


Figure 1. *HST* images of three Cepheids whose hot companions were resolved in WFC3 images: η Aql (left), V659 Cen (center), and S Nor (right). These are V-band images, with a logarithmic stretch. Each frame is $4'' \times 4''$. Companions are circled in green.

(A color version of this figure is available in the online journal.)

course, only the instantaneous projected separations; however, we will be examining the distribution of the logarithm of separations, so this is a small uncertainty.

For completeness, in Table 2 we also include the wider resolved δ Cep system and the close W Sgr, both of which were discussed in Section 2. (The companion of δ Cep was outside our WFC3 field of view, and the companion of W Sgr was within the saturated pixels close to the Cepheid.)

For η Aql, Benedict et al. (2007) found perturbations in their *HST* FGS measurements within a couple of years, implying a companion in a relatively short-period orbit. Since we have now directly resolved the hottest companion in the system (Table 2) with a much larger separation/period, we conclude that the system is triple. The Cepheid S Nor is a member of a cluster, increasing the probability of a chance optical alignment. However, the small separation ($0''.9$) makes a physical association highly probable. S Nor also has a hot companion at a much wider separation of $36''$ (Evans & Udalski 1994), making it a possible triple. In this case, given the high stellar density in the cluster, this could be a chance alignment.

3.2.2. Approximate Orbital Periods

We used the angular separations in Table 2, along with the secondary masses from Table 1, and the primary masses and distances from Table 3 (below), to calculate nominal orbital periods by equating the projected angular separation to the semimajor axis, a , of the putative orbit. The resulting $\log P$ values are given in Column 7 of Table 1. To distinguish these from the directly determined spectroscopic periods (Section 3.1), the $\log P$ values are given to only one decimal place. Column 8 of Table 1 gives the values of $\log a$, again to only one decimal.

3.3. Cepheids with and without Detected Orbital Motion

Of the 18 systems in Table 1, 9 have known orbital periods, and 5 have been spatially resolved, as recounted above. The remaining four stars (SU Cas, BP Cir, T Mon, and T Vul) have detected hot companions whose temperatures and luminosities are consistent with the distances of the Cepheids (Evans 1992b, 1992c, 1994; Evans et al. 1999). While a chance alignment between a B or A star and a Cepheid is highly improbable, orbital motion would be conclusive proof of physical association. In this subsection we discuss what is known from RVs in the literature, and what limits can be put on the separations.

1. *SU Cas*. RVs have been measured in a number of studies. The best claim for the detection of orbital motion is by Gorynya et al. (1996), who rate SU Cas as a possible spectroscopic binary. We have tested this by comparing two seasons of accurate data from the same group (Moscow

Table 2
Cepheids with Resolved Companions

Star	WFC3 Obs. Date	Sep. ($''$)	Sep. (AU)	Ref.
η Aql	2010 Nov 20	0.66	180	1
V659 Cen	2011 Jun 5	0.63	474	1
S Nor	2011 Apr 1	0.90	817	1
δ Cep	...	40.0	10360	2
W Sgr	...	0.16	65	3

References. (1) This paper; (2) Benedict et al. 2002; (3) Evans et al. 2009.

University) so that instrumental differences should be minimal. Typical uncertainties of their annual velocities are $\pm 1 \text{ km s}^{-1}$. We have chosen data from two years (1995 and 1997) which are predicted to have orbital velocities close to minimum and maximum according to their proposed orbit, and a velocity difference of 6 km s^{-1} . When the pulsation velocity curves from the two years are overlaid, there is no appreciable difference, certainly nothing as large as that predicted by the orbit. We conclude that orbital motion has *not* been detected convincingly.

2. *BP Cir*. RV data have been discussed by Petterson et al. (2004). The original velocity data are from Balona (1981), and have standard deviations of 2.5 km s^{-1} (Stobie & Balona 1979). Data were added from the Mount John University Observatory, with the final three years providing an accuracy of $\pm 0.3 \text{ km s}^{-1}$. Petterson et al. estimate the orbital motion to be greater than 5 km s^{-1} . Orbital motion appears to be seen on timescales of decades, providing some constraint on the period, but further observations are needed for confirmation.
3. *T Mon*. RV variation is seen, although the orbital period is too long for a determination at present. Preliminary estimates of the period are between 90 and 260 yr (Evans et al. 1999).
4. *T Vul*. It has been suggested several times that orbital motion may have been detected in RV measurements. Bersier et al. (1994) discuss this on the basis of 11 yr of CORAVEL data. They find a standard deviation of the data around the pulsation Fourier curve of only 0.55 km s^{-1} . There are some limitations in the spacing of the data, in that the CORAVEL observations were made only in the autumn and the most likely suggested period is close to 2 yr. However, there is no evidence of orbital motion at the level of $< 1 \text{ km s}^{-1}$. Kiss (1998) and Kiss & Vinko (2000) extended the data series to 20 yr using RVs from David Dunlap Observatory spectra. Figure 3 in Kiss & Vinko shows no indication of orbital motion, only a possible small difference in the shape of the curve from the analytic fit to the CORAVEL data. We conclude that the highest-quality data show no orbital motion.

3.3.1. Approximate Orbital Periods

While these four stars do not have a period or separation as well defined as either the stars with RV orbits or the resolved stars, there is information about both these quantities that provides significant constraints. For the two stars with orbital motion, BP Cir and T Mon, we can assign reasonable estimates of the periods from the discussion in the previous section which should not result in large errors in the distribution of $\log P$ for the entire sample. For BP Cir, an orbital period of 20 yr ($\log P = 3.9$ in days) is plausible for the observed orbital motion. For T Mon,

Table 3
Physical Properties of the Cepheids

Star	P_{puls} (days)	M_V (mag)	$E(B - V)$ (mag)	$(B - V)_0$ (mag)	$\langle V \rangle_0$ (mag)	BC (mag)	$\log L/L_\odot$	d (pc)	$M/M_\odot$
η Aql	7.17	−3.70	0.12	0.71	3.48	−0.110	3.42	273	5.7
U Aql	7.02	−3.68	0.35	0.70	5.26	−0.105	3.41	614	5.7
RX Cam	7.91	−3.80	0.63	0.61	5.47	−0.067	3.44	714	5.8
SU Cas	2.74 ^a	−2.68	0.23	0.49	5.19	−0.027	2.97	375	4.2
V659 Cen	5.62	−3.44	0.21	0.61	5.94	−0.067	3.29	752	5.2
δ Cep	5.36	−3.39	0.09	0.57	3.68	−0.053	3.27	259	5.2
AX Cir	5.27	−3.37	0.25	0.67	5.23	−0.091	3.28	525	5.2
BP Cir	3.39 ^a	−2.91	0.32	0.51	6.60	−0.033	3.07	798	4.5
SU Cyg	3.84	−3.04	0.08	0.56	6.62	−0.049	3.13	855	4.7
V1334 Cyg	4.74 ^a	−3.26	0.07	0.51	5.74	−0.033	3.21	631	4.9
T Mon	27.02	−5.10	0.14	1.09	5.66	−0.416	4.10	1419	9.1
S Mus	9.65	−4.01	0.21	0.69	5.47	−0.100	3.54	787	6.2
S Nor	9.75	−4.02	0.19	0.77	5.77	−0.153	3.56	908	6.3
AW Per	6.46	−3.59	0.53	0.57	5.72	−0.053	3.35	728	5.4
W Sgr	7.59	−3.76	0.11	0.65	4.30	−0.083	3.43	409	5.8
V350 Sgr	5.15	−3.35	0.32	0.55	6.41	−0.046	3.25	895	5.1
V636 Sco	6.79	−3.64	0.20	0.73	5.96	−0.119	3.40	832	5.6
T Vul	4.43	−3.19	0.06	0.64	5.41	−0.079	3.21	561	4.9

Note. ^a First-overtone Cepheid, for which the listed period has been “fundamentalized” as discussed in the text.

a period of ~ 150 yr ($\log P = 4.7$ in days) is in the middle of the range of plausible orbital periods.

The remaining two stars—SU Cas and T Vul—appear to lie in the orbital separation range between the stars with known orbital periods and those for which the companions are separated widely enough to be resolved with *HST* or from the ground. Neither star was resolved in our WFC3 survey. We estimate that these comparatively bright companions would have been resolved for a separation of more than $0''.3$. Using the distances to the two stars as well as the masses (Tables 1 and 3) results in upper limits for $\log P$ of 5.2 for SU Cas and 5.5 for T Vul. For lower limits of the separation, we use RV observations. As discussed above for SU Cas, orbital motion was not seen in recent RV data (Gorjnya et al. 1996). There are also earlier high-quality RV data. Based in particular on the discussion of Niva & Schmidt (1979) we conclude that no orbital motion has been detected over 40 yr, and use that as an orbital period lower limit ($\log P = 4.2$ in days). Thus the available data constrain the periods for both stars to lie between 10^4 and 3×10^5 days. In Table 1 we assign SU Cas to $\log P = 5.1$ and T Vul to $\log P = 4.9$.

4. MASS RATIOS

The next parameter of the sample to examine is the mass ratio $q = M_2/M_1$, where M_2 is the mass of the secondary companion and M_1 is the mass of the Cepheid. One of the strengths of the present study is that the masses of *both* the primary and the secondary can be inferred from uncontaminated spectra and photometry of both stars in the visible and the UV, respectively. Furthermore, this direct access to the parameters of both components is available at *all* orbital separations, which is unique among samples of massive stars.

Table 3 lists the relevant parameters for the Cepheid components, which have been determined as follows. Column 2: pulsation periods; three of the stars (SU Cas, BP Cir, and V1334 Cyg) pulsate in the first overtone, so the listed period has been “fundamentalized” using the relation from Alcock et al. (1995):

$$P_1/P_0 = 0.720 - 0.027 \log P_0,$$

where P_1 is the first overtone-mode period and P_0 is the fundamental period. Column 3: unreddened visual absolute magnitude, M_V , derived from the Leavitt (period–luminosity) relation as given by Benedict et al. (2007):

$$M_V = -4.05 - 2.43(\log P - 1.0).$$

Columns 4–6: values of $E(B - V)$, $(B - V)_0$, and $\langle V \rangle_0$, which have been corrected for the effect of the companion and are taken from the same sources as the companion spectral types (or can be directly traced from those references). Corrected photometry for S Mus is from Evans et al. (1994). The exception is δ Cep, where the companion does not affect these values because it is well resolved; its parameters have been taken from the Galactic Cepheid database⁷ (Fernie et al. 1995). For all of the Cepheids, $\langle V \rangle_0$ has been computed using $R = A_V/E(B - V) = 3.46$, appropriate for Cepheids (Evans 1991). Columns 7 and 8: bolometric correction, taken from Flower (1996), and the resulting value of $\log L/L_\odot$. Column 9: distance, calculated from M_V and $\langle V \rangle_0$. Column 10: mass, computed using the models of Prada Moroni et al. (2012) with moderate convective overshoot (0.2 times the pressure scale height at the edge of the convective core on the main sequence; “noncanonical”; G. Bono 2012, private communication), from the relation

$$\log M/M_\odot = 0.297 \log L/L_\odot - 0.259.$$

Using the Cepheid masses in the final column of Table 3, we calculated values of the mass ratio q , which are listed in Column 9 of Table 1.

Figure 2 shows the distribution of Cepheid masses (solid red line) and companion masses (dashed black line) in our sample, which, of course, is truncated for companion masses lower than $2 M_\odot$. Figure 3 plots the companion masses against the Cepheid masses, and indicates no strong correlation between them. In fact, two of the most massive Cepheids (S Mus and S Nor, at masses of 6.2 and 6.3 $M_\odot$, respectively) have companions covering nearly the full range of companion masses (5.3 and 2.4 $M_\odot$ respectively.)

⁷ Available at <http://www.astro.utoronto.ca/DDO/research/cepheids>.

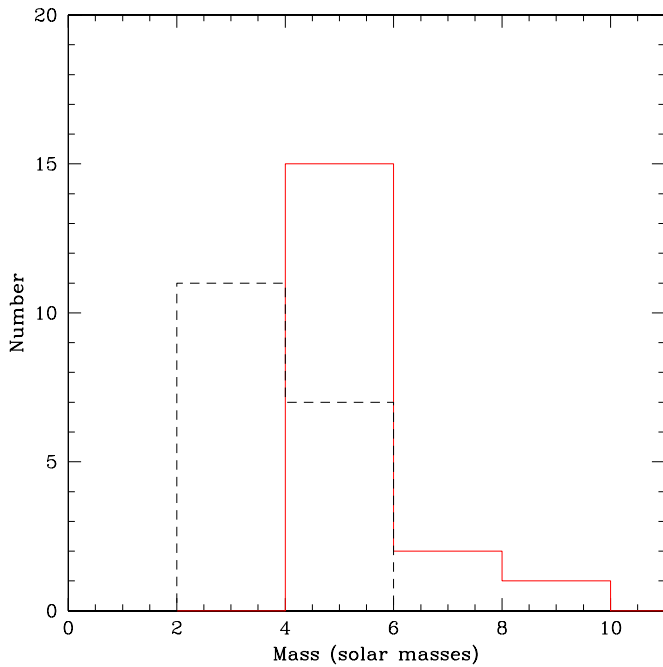


Figure 2. Distribution of masses: Cepheid masses: solid line; companion masses: dashed line.

(A color version of this figure is available in the online journal.)

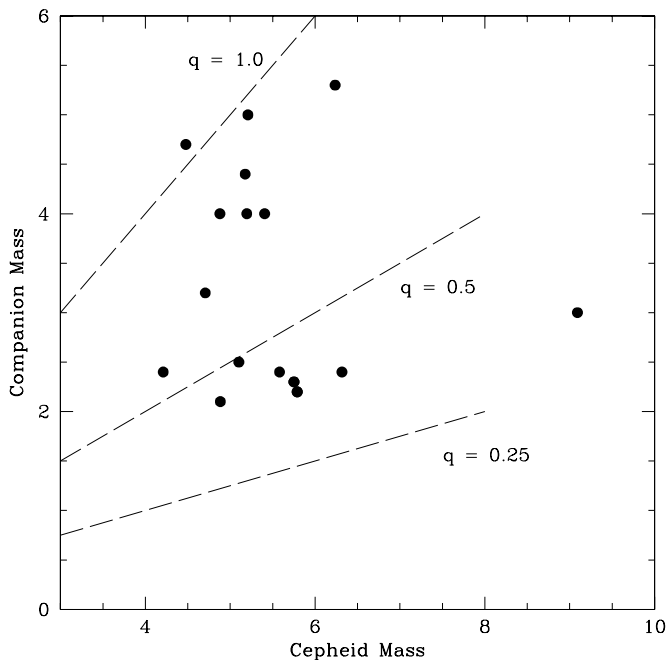


Figure 3. Mass of the companion as a function of the mass of the Cepheid. Masses in all figures are in solar masses. Dashed lines indicate mass ratios.

5. DISTRIBUTION OF SEPARATIONS AND ORBITAL PERIODS

Table 1 provides the information for a study of the distribution of orbital separations and periods. However, we must keep in mind two sample biases. (1) Although the photometric approach to creating the sample means that companions at any separation are equally likely to be identified, the sample contains only companions hotter than early A spectral type, with the least massive being $2.1 M_{\odot}$ (T Vul B). (2) Stars evolving off the main sequence in relatively close orbits will undergo Roche-

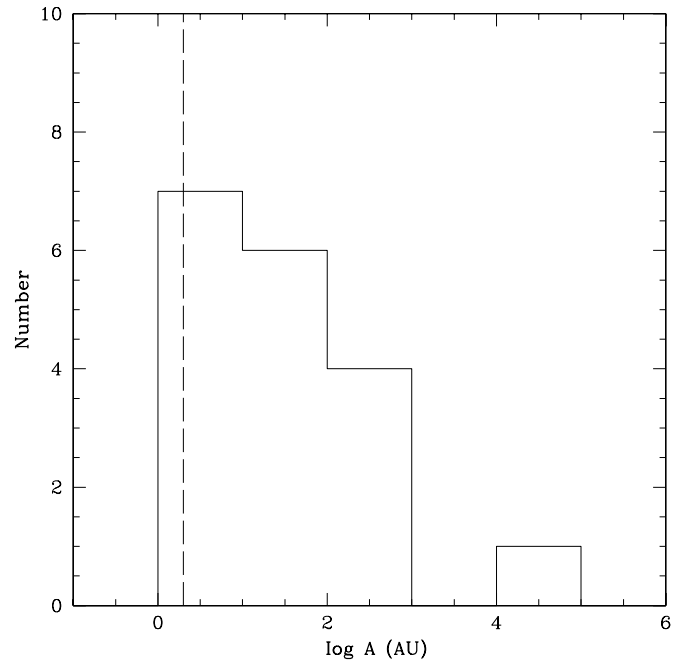


Figure 4. Distribution of separations ($\log a$ in AU). The dashed vertical line indicates the separation for periods of 1 yr, below which Cepheid orbits have been disrupted by Roche-lobe overflow.

lobe overflow and the subsequent evolution of the system will be drastically altered. For Cepheids we have a good estimation of where this effect sets in. Z Lac—not in our sample because the mass of its unseen companion has an upper limit of $1.9 M_{\odot}$ —is the Cepheid with the shortest known orbital period (382 days; Sugars & Evans 1996). It is also the only known Pop I classical Cepheid binary orbit with zero eccentricity, suggesting that it was circularized, appropriate for a system that just missed significant Roche-lobe overflow.

The orbital separations in Column 8 of Table 1 were calculated as follows. Directly measured (projected) separations for the five resolved binaries have been taken from Table 2. For the remaining objects, the semimajor axes were calculated from the masses and orbital periods. Values of the separation from measured orbital periods are given to two decimal places, and from projected separations or the estimated periods of SU Cas and T Vul to one decimal place. For the triple systems the total mass of the system, and hence the separation, will be underestimated since we do not know the mass of the third star. However, since we know the masses of the two most massive stars in the system, this is a relatively small underestimate. Figure 4 shows the distribution of separations. The vertical dashed line marks the cutoff in separations for periods of less than a year.

The distribution of orbital periods for our Cepheids is shown as the red histogram in Figure 5. We know the bin for $\log P = 2-3$ is incomplete due to the destruction of short-period orbits (Sugars & Evans 1996). Because the shortest orbital period for a Pop I classical Cepheid (Z Lac, $\log P = 2.58$) falls in the center of this bin, we have doubled the number of Cepheids in that bin to account for stars removed from the sample. For comparison, we show (dashed black histogram) the distribution of orbital separations for solar-mass stars from Raghavan et al. (2010). We have used their Figure 11 to create a sample with $q > 0.4$ for comparison with the Cepheid sample. (Binaries in the Raghavan sample with $\log P < 2$ have been omitted.)

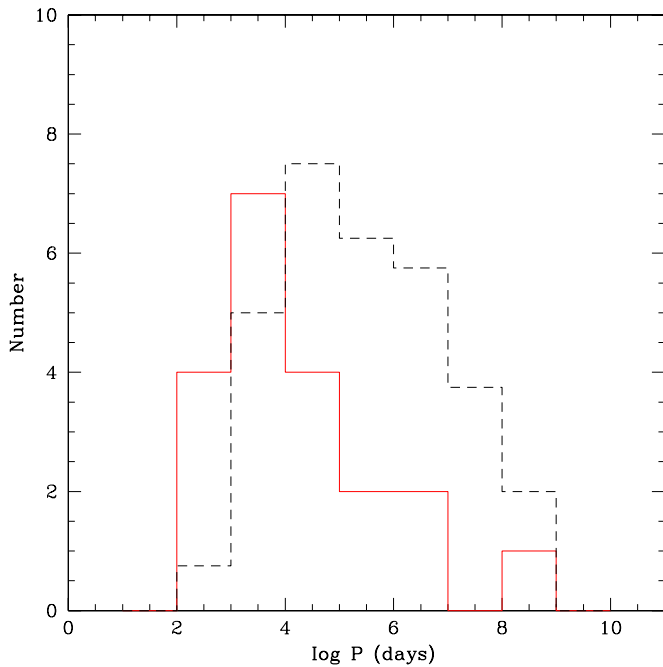


Figure 5. Distribution of orbital periods. Cepheids: solid red line; solar mass stars: dashed black line. Both samples include only systems with $q = M_2/M_1$ greater than 0.3–0.4. Binaries in the Raghavan sample with $\log P < 2$ are not shown.

(A color version of this figure is available in the online journal.)

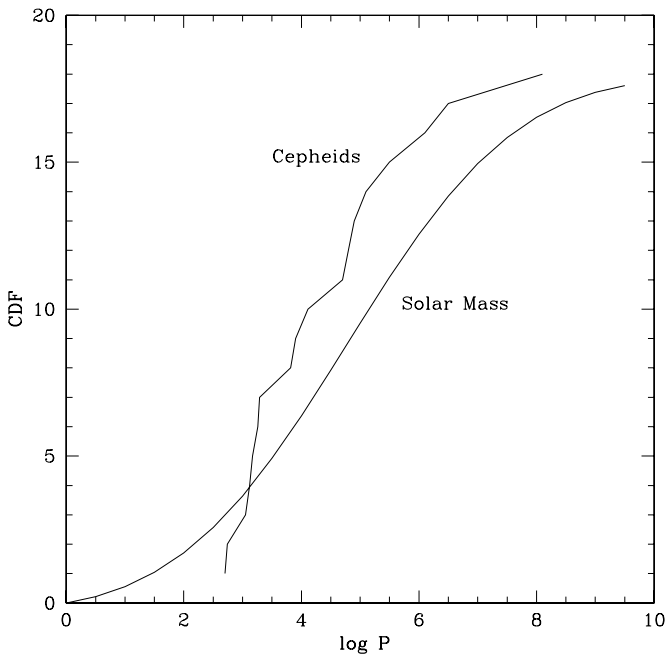


Figure 6. Cumulative distribution function (CDF) of Cepheid orbital periods and solar mass orbital periods as a function of $\log P$ (in days).

The difference between the distributions of orbital periods for $5 M_\odot$ and $1 M_\odot$ in Figure 5 is striking in that the more massive stars are concentrated at shorter periods than are the solar-mass stars. The difference in the distributions is confirmed by the cumulative distribution functions (CDFs) plotted in Figure 6, showing the observed Cepheid distribution compared with the Gaussian fitted by Raghavan et al. (2010) to solar-mass stars. A Kolmogorov–Smirnov (K-S) test confirms that the Cepheid CDF is significantly different from the CDF created from

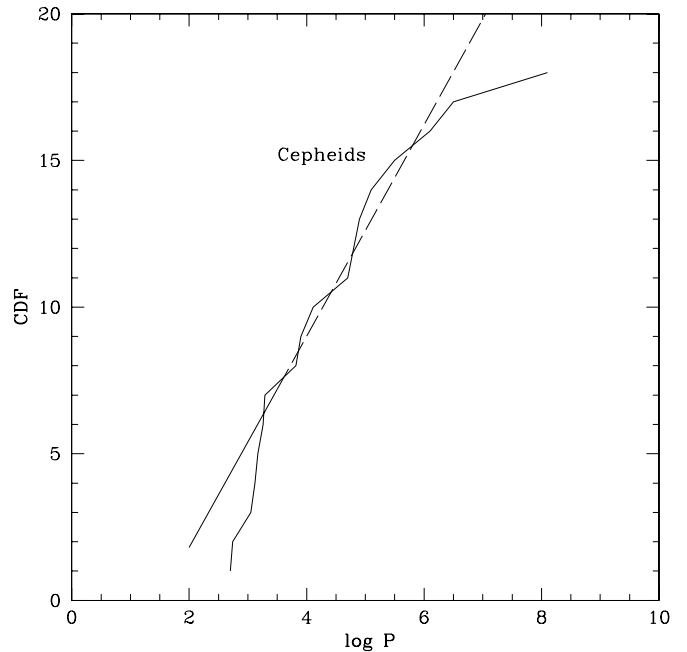


Figure 7. Cumulative distribution function (CDF) of Cepheid periods compared with binaries among massive stars from Sana & Evans (2011). The slope of the broken “Öpik law” for Sana & Evans’ longer periods is shown by the line. It is solid for the range of periods covered by the Sana & Evans sample ($\log P = 2$ –3.5) and dashed for the extrapolation to longer periods.

Figure 11 of Raghavan et al. for the same range of mass ratios and separations. However, if $\log P$ is arbitrarily increased for the Cepheids, the form of the CDF closely matches that for the solar-mass stars. Sana & Evans (2011) have assembled binary/multiple properties of O and early B (down to B3) stars from the field and a large sample of galactic clusters. Figure 7 shows the Cepheid CDF compared with the Sana & Evans (2011) results. They fit the data with a “broken Öpik’s law” divided for periods longer and shorter than 10 days. (Öpik (1924), as discussed by Sana & Evans, models the distribution of periods to be flat in $\log P$ space.) Figure 7 shows the slope of their CDF (defined for $\log P = 1.0$ –3.5, but shown in the plot from $\log P = 2.0$ to 3.5, and extrapolated to longer periods). The Cepheid data fit the extrapolation well to about $\log P = 6.0$. The decline at higher periods matches the expectation from the Gaussian fit to solar mass stars. For $\log P < 2.5$ Cepheid binaries have low frequency because Roche-lobe overflow occurs during post-main-sequence evolution.

One parameter that is similar between 5 and $1 M_\odot$ stars is the binary frequency. The binary frequencies for periods longer than a year and $q > 0.4$ are 24% for Cepheids and 27% for solar-mass stars.

6. DISTRIBUTION OF MASS RATIOS

The mass ratios, q , in Table 1 have been computed directly from *uncontaminated* information about both components. The mass ratio of BP Cir has the unphysical result that it is slightly larger than 1.0 ($q = 1.05$). We take this to indicate simply an uncertainty in the derivation of the masses, and that the mass of the Cepheid is only very slightly larger than that of the companion. Figure 8 shows the frequency distribution of q . Although the sample is modest in size, it is well defined. The $q = 0.3$ –0.4 bin is presumably somewhat incomplete, since the sample criterion was based on the mass of the secondary,

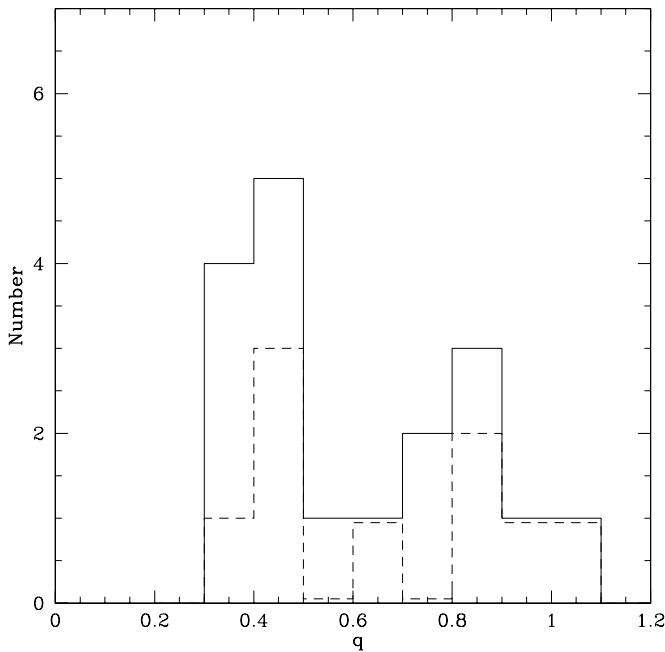


Figure 8. Distribution of mass ratios (solid: all stars; dashed: $\log P < 4$). Histogram heights have been slightly adjusted for clarity.

and the resulting q also depends on the mass of the primary. The highest frequency is for systems in the smallest two bins ($q = 0.3\text{--}0.5$). One interpretation of the Cepheid distribution would be a bimodal one, with a concentration at large q (equal masses) and another one around $q \simeq 0.4$, with fewer systems in between.

Does the distribution of mass ratios depend on the separations of the systems? Figure 8 compares the total sample with the sample of closer systems ($\log P < 4$; scaled by a factor of 2). The largest change is in the smaller- q bins. That is, there is an indication that closer systems are more likely to have larger q than wider systems (remembering that the Cepheid sample is limited to systems of a year or longer, i.e., $\log P > 2.6$.)

Cepheids (Evans et al. 2005) and also solar-mass stars (Raghavan et al. 2010) have a high proportion of triple systems among the multiple systems. The sample discussed here is a particularly good one for examining the effects of triple systems, since information is available about each secondary mass and frequently the velocity of the secondary, which increases the probability of identifying triple systems. Columns 10 and 11 in Table 1 indicate which members of the Cepheid sample are known to be triple systems, and the source of this information. (V1334 Cyg is not classified as a triple as discussed above.) There may be additional unrecognized triple systems in the sample since complete detection requires extensive observation of both stars in a binary. Figure 9 shows the distribution of mass ratios for the known members of triple systems compared with the full sample. The large- q systems do *not* appear in the sample of triples. That is, there is an indication that in a triple system, the mass ratio between the most massive and the second most massive star in the system is not as large as in a simple binary system, presumably frequently somewhat compensated for by the mass of the third star in the system.

The comparison between the cumulative distributions is shown in Figure 10. As in Figures 8 and 9, differences are suggestive but not statistically significant in a K-S test.

How does the distribution of mass ratios for our Cepheids compare with those for other stellar classes? Sana & Evans

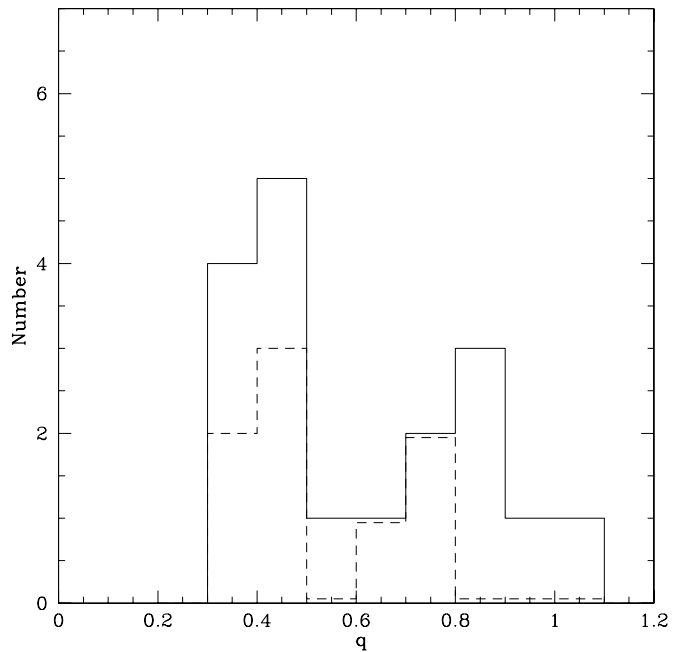


Figure 9. Distribution of mass ratios (solid: all stars; dashed: triple systems).

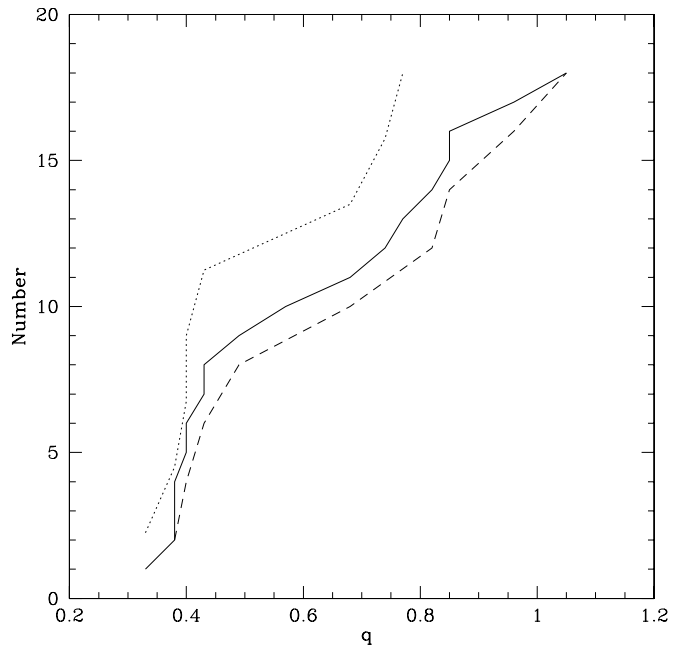


Figure 10. Cumulative distribution of mass ratios. Solid: all stars; dashed: $\log P < 4$; dotted: triple systems. The samples of short period binaries and triple systems have been scaled by 2.0 and 2.25, respectively.

(2011) find that for their O-star sample, a uniform distribution in q fits the data well. This is shown in Figure 11, compared with the distribution for the Cepheid sample. The normalization is approximate because the Cepheid study does not include small- q systems. For solar-mass stars, Duquennoy & Mayor (1991) concluded that the q distribution is very similar to the initial mass function, with few systems near $q = 1$ and many with small q . The recent, updated sample by Raghavan et al. (2010) came to different conclusions. Figure 11 also shows the distribution of q values for the Raghavan et al. sample of solar-mass stars. For the comparison we have used data from their Figure 16 (left) binary systems. Their study illustrates very

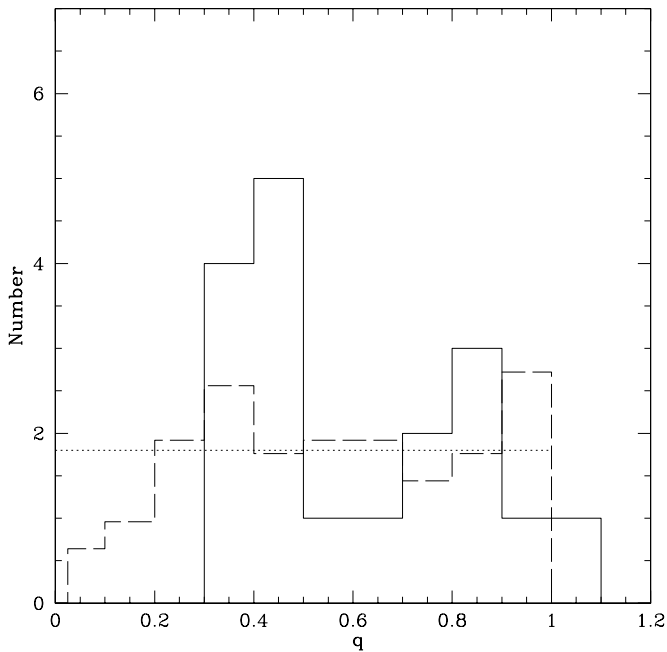


Figure 11. Distribution of mass ratios. Solid line: Cepheids, Figure 8; dashed line: Raghavan solar-mass binaries; dotted line: Sana & Evans O stars.

well the complexity presented by components from the combination of binary and multiple systems. They have looked at the q distribution for binary and multiple systems divided in two ways (within a spectroscopic binary and also the ratio of the combined spectroscopic binary mass to the mass of the visual binary secondary). The first approach (their Figure 16b) gives a distribution very similar to that of their binary systems. We do not have information comparable to the second approach (their Figure 16c). Therefore we have adopted their distribution for binary systems as representative of their findings. We have rebinned it into bins covering 0.1 in q and approximately scaled it (Figure 11). This treatment of the data decreases the prominence of the peak at equal masses ($q = 1$) for the solar-mass stars, which makes the distribution reasonably similar to the uniform distribution for the O stars. The largest peak in the Cepheid data is at the smallest q values in our sample. Further discussion of the distribution of q values is deferred to a later paper in this series, which will deal with a larger range of mass ratios.

An important parameter to investigate further with this sample is whether there is any difference in binary/multiple characteristics between close and wide systems. Figures 12 and 13 further explore the comparison made in Figure 8. Figure 12 shows the distributions of mass ratios for stars with $\log P > 4$ and $\log P < 4$. The suggestion that closer systems have larger mass ratios is confirmed in Figure 13, which compares the cumulative distributions for these two period groups.

An important question in interpreting the distributions in Figures 12 and 13 is whether they trace back to the original formation state, or whether there has been any dynamical evolution in the periods and separations of the systems after formation. One approach to this problem is to compare the properties of binary and triple systems. Systems with three (or more) components can have interactions between the stars that will alter the original configuration (even sometimes ejecting a component), which does not happen in purely binary systems. As discussed above, we have identified a number of triple

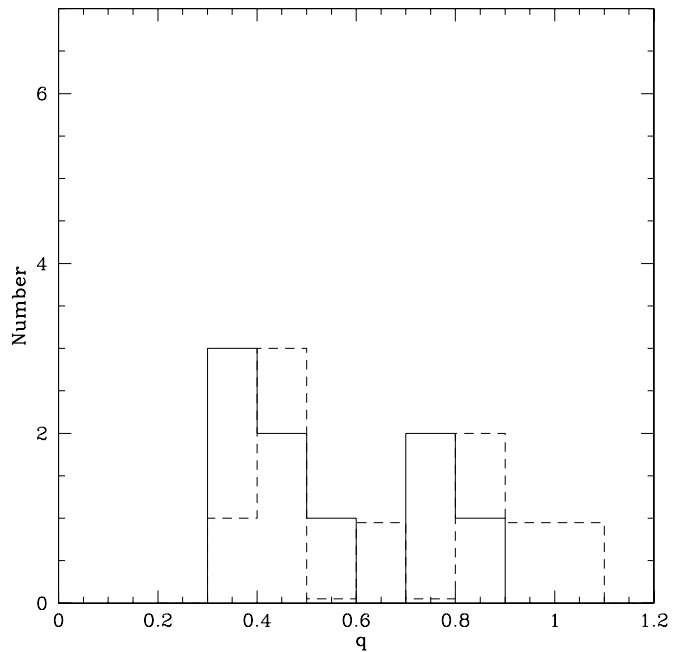


Figure 12. Distribution of mass ratios divided into period groups ($\log P < 4$: dashed line; $\log P > 4$: solid line). Periods are in days.

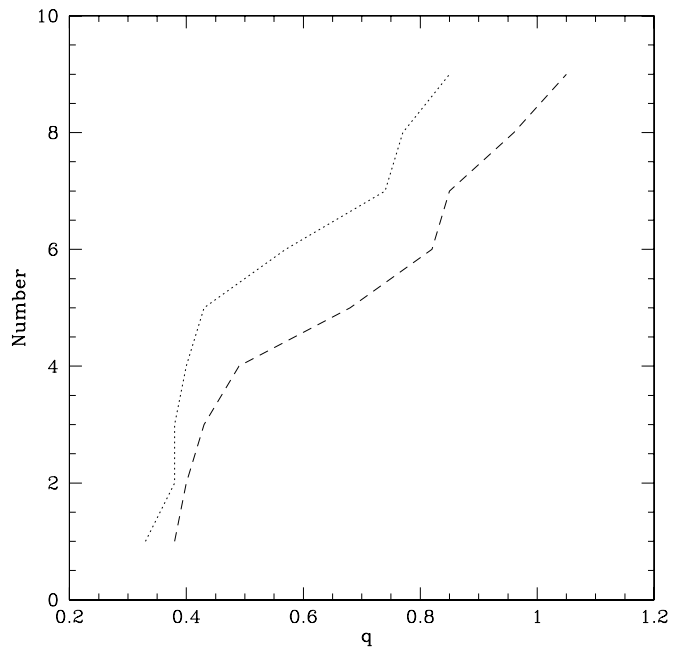


Figure 13. Cumulative distribution of mass ratios divided into period groups ($\log P < 4$: dashed line; $\log P > 4$: dotted line). Periods are in days.

systems within the sample. Figure 14 compares the distribution of mass ratio and $\log P$ for binary and triple systems. As noted above, the binary systems have higher q on average. Using the binary sample as “dynamically unevolved,” Figure 14 shows that it contains wide systems as well as close ones, similar to the triple systems. That is, the indication is that the wide systems are not exclusively those with a component moved out by dynamical interaction. There are two caveats to this first exploration. Some of the binaries may have undetected third components (despite the extensive multi-wavelength information on the sample). However, the binary sample should be dominated by systems that have not had internal interactions between components. Second, of course, it is possible that a previous component has

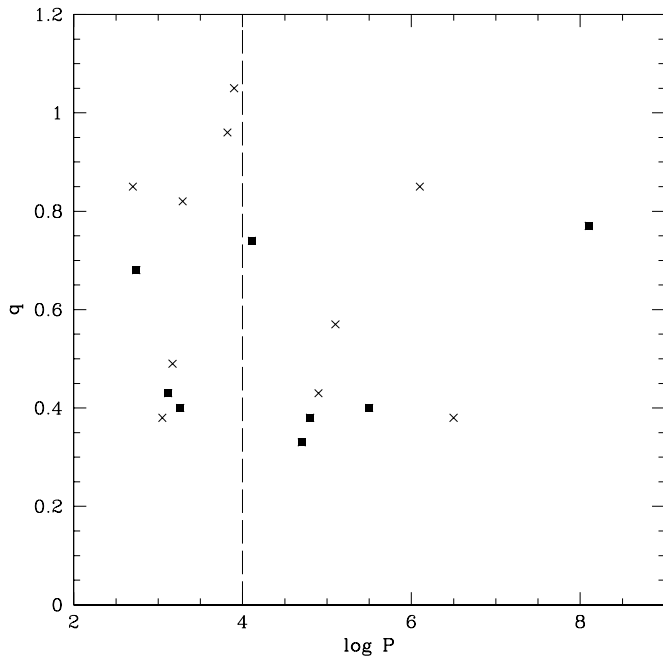


Figure 14. Mass ratio q as a function of $\log P$ (in days). Systems known to be triple systems are filled squares; binary systems are X's. The dashed vertical line is the dividing line in previous figures at $\log P = 4$ (period in days).

been ejected, but this could have happened in either the binary or triple sample.

7. SUMMARY

We have used an *IUE* survey of Cepheids to create a list of binary systems with mass ratios $q \geq 0.4$, which is complete for all separations. We have combined separations from resolved companions from an *HST* imaging survey with orbits from the literature and RV data to derive the distribution of orbital separations for the sample. The $5 M_{\odot}$ Cepheids are found to have systematically shorter orbital periods than the sample of $1 M_{\odot}$ stars from Raghavan et al. (2010), confirmed as statistically significant by a K-S test (Figure 5). The distribution of mass ratios is also presented, with suggestions that closer systems have larger mass ratios and also that triple systems have smaller secondary to primary mass ratios. The distribution of mass ratios as a function of orbital separation, however, is the same whether a system is a binary or a triple.

These results for $5 M_{\odot}$ for all separations and mass ratios $q \geq 0.4$ is the first step to be followed by studies of resolved companions, low-mass companions (of late B stars), and RV observations. The picture that is thus built up of binary properties will be compared with those of higher and lower mass stars for insights into star formation as well as future evolution.

It is a pleasure to thank H. Harris and K. Kratter for valuable discussions. *IUE* continues to provide a valuable foundation for Cepheid companion studies. Support for this work was also provided by HST grant GO-12215.01-A and from the Chandra X-Ray Center NASA Contract NAS8-03060. VizieR and SIMBAD were used in the preparation of this study.

Facilities: HST (WFC3), *IUE*

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