THE ASTROPHYSICAL JOURNAL, 490:328–342, 1997 November 20

THE "MASS DISCREPANCY" FOR MASSIVE STARS: TESTS OF MODELS USING SPECTROSCOPIC BINARIES

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Received 1997 January 27; accepted 1997 June 26

ABSTRACT

Stellar evolutionary models are often used to infer a star's mass via its luminosity, but empirical checks on the accuracy of the theoretical mass-luminosity relation for very massive stars have been lacking. This is of particular concern given that modern atmosphere models yield systematically smaller masses for massive stars than do evolutionary models, with the discrepancy being a factor of 2 for Of stars. We attempt to resolve this mass discrepancy by obtaining new, high-resolution optical data on seven early-type spectroscopic binaries: V453 Cyg, HD 191201, V382 Cyg, Y Cyg, HD 206267, DH Cep, and AH Cep. Our study produces improved spectral subtypes for the components of these systems, which are crucial for evaluating their luminosities and locations in the H-R diagram. Our radial velocity study utilizes a measuring method that explicitly accounts for the effects of pair blending. We combine our new orbit solutions with existing data on inclinations and distances when available to compare the orbital masses with evolutionary models, and we find good agreement in all cases where the stars are noninteracting. (The components of V382 Cyg and DH Cep fill their Roche lobes, and in both cases we find masses substantially lower than the masses inferred from evolutionary tracks, suggesting that significant material has been lost rather than transferred. We confirm that this same trend exists for other systems drawn from the literature.) Our own data extends to only 15 $M_{\odot}$, although photometric inclination determinations for HD 191201 and HD 206267 should prove possible and will provide examples of higher mass systems. We briefly discuss suitable systems from the literature and conclude that orbit solutions provide good agreement with the evolutionary models to 25 $M_{\odot}$. Beyond this, most known binaries either fill their Roche lobes or have other complications. We also discuss five systems for which our improved data and analysis failed to yield acceptable orbit solutions: EO Aur, IU Aur, V640 Mon (Plaskett's star), LY Aur, and 29 UW CMa all remained intractable, despite improved data.

Subject headings: binaries: spectroscopic — stars: early-type — stars: evolution — stars: fundamental parameters

1. INTRODUCTION

The past 25 years have seen a revolution in our understanding of stars at the upper left of the H-R diagram, where extremes of temperature, luminosity, and mass pose significant challenges to theoretical astrophysics. Non-LTE stellar atmosphere calculations, beginning with Auer & Mihalas (1972), have allowed the solid establishment of an effective temperature scale for O-type stars (Conti & Alschuler 1971; Conti 1973). These early models included only hydrogen and helium, but modern models include the myriad transitions of more complicated atoms (Puls et al. 1996; see also the review by Kudritzki 1991). For stellar interiors, the models of de Loore, de Greve, & Lamers (1977), Chiosi, Nasi, & Sreenivasan (1978), and Brunish & Truran (1982a, 1982b) demonstrated the importance of mass loss on main-sequence evolution, leading to the current generation of evolutionary tracks by the Geneva group (Maeder & Meynet 1988; Schaller et al. 1992; Schaerer et al. 1993; see also the review by Maeder & Conti 1994). However, there appears to be a fundamental quandary posed by a comparison of modern hot-star atmosphere models and that of stellar evolutionary models.

At the first Boulder-Munich workshop on hot luminous stars, Kudritzki (1990) described a method for determining masses from stellar atmosphere models. Line fitting yields values of the effective temperature ($T_{\rm eff}$) and surface gravity

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(g). If the distance and reddening of the star is known, then photometry leads to the star's luminosity, L, since the bolometric correction (critical for hot stars) is also known from the atmosphere models once $T_{\rm eff}$ and g are fixed. Since $L \sim R^2 \times T_{\rm eff}^4$, R can now be determined, and since $g \sim M/R^2$, the star's mass can, in principle, be found (Kudritzki & Hummer 1990; Kudritzki 1991). Even if the star's distance is unknown, the mass can be found if the terminal velocity (v_∞) of the stellar wind can be measured, as v_∞ is linearly proportional to the escape velocity [$v_{\rm esc} \sim (M/R)^{1/2}$]: $v_\infty = v_{\rm esc} \times f$, where f is highly insensitive to stellar parameters for high-mass stars, and has a numerical value of about 3.0 for Galactic abundances and 2.2 for SMC abundances; see Figure 13 of Kudritzki et al. (1989). Once $v_{\rm esc}$ and g are both known, the mass can be determined from $M \sim v_{\rm esc}^4/g$. Kudritzki (1991) emphasizes that these two spectroscopic methods agree and that since v_∞ can usually be measured to good precision using UV resonance lines, the second method is in principle more accurate despite the fourth-power dependence.

However, Herrero et al. (1992) called attention to a significant "mass discrepancy": the stellar masses derived by these spectroscopic methods are systematically smaller than those inferred from stellar evolutionary tracks using the star's luminosity and effective temperatures. There is reasonably good agreement for some stars of luminosity class "V," but the discrepancy is a factor of 2 or more for Of stars (Herrero, Kudritzki, & Vilchez 1990; Herrero et al. 1992; Puls et al. 1996). Even stars of luminosity class "V" can show differences of a factor greater than 1.5. (See Table 4 and Fig. 14 of Herrero et al. 1992.)

Our interest in resolving this discrepancy stems in part comes from recent extensive work on determining the initial mass functions (IMF) for stars in the Magellanic Clouds (Garmany, Parker, & Massey 1989a; Massey et al. 1989b, 1995b) and Galactic OB associations (Massey & Thompson 1991; Massey & Johnson 1993; Hillenbrand et al. 1993; Massey et al. 1995a). In these studies, the spectral type (including the luminosity class) provides estimates of $T_{\rm eff}$ and g and, hence, the all-important bolometric correction. Combined with a distance, (reddening-corrected) photometry then fixes a star's location in the theoretical H-R diagram, and stellar evolutionary tracks are used to infer masses. Although not as precise, in theory, as Kudritski's (1991) "quantitative spectroscopy" approach, the use of the intermediate step of spectral types has the advantage of not requiring the same signal-to-noise data needed for careful line fitting and provides a simple means for revision were the effective temperature scale of O and early B stars to be improved. Massey et al. (1995a, 1995b) emphasize that the differential comparisons in the IMF slope (cluster vs. field; Milky Way vs. Magellanic Clouds) should also remain valid despite any uncertainties in the evolutionary models used to derive the actual masses, but it is of interest to determine whether the mass estimates obtained in such studies are actually a factor of 2 too high! Tests of evolutionary tracks of the Geneva group (e.g., Maeder & Meynet 1988; Schaller et al. 1992; Schaerer et al. 1993) in the *field* of the Magellanic Clouds (i.e., of a mixed-age population) have demonstrated that the Geneva evolution models do an excellent job of reproducing the observed distribution of massive stars across the main sequence, i.e., that the relative lifetimes at various luminosities and temperatures were correct (Massey et al. 1995b). However, until now it has not been possible to establish whether the basic relation between mass and luminosity predicted by the models can be substantiated observationally.

To resolve this issue, we turn to a third, and more fundamental, method, using massive binaries with known distances to determine the mass-luminosity (M-L) relationship directly. The M-L relationship is one of the fundamental tests of stellar interior models, and good accord has long been achieved for stars of intermediate mass (Schwarzschild 1958). However, this has been difficult to establish for massive stars, owing to the rarity and complexity of O- and B-type double-lined binaries. Such systems are often interacting, having poorly determined distances or orbital inclinations, or the analysis is complicated by outflowing stellar winds and/or gas streamers. For instance, in the *Eighth Catalogue of the Orbital Elements of Spectroscopic Binary Systems*, Batten, Fletcher, & MacCarthy (1989) list only 45 early-type, double-lined systems with minimum masses greater than 10 $M_\odot$. Of these, 26 of these orbits are given quality ratings of "d" or "e," corresponding to "poor" or "very poor and unreliable." (Only one such system has a "definitive" rating.) In addition, the spectral types for the individual components are often poorly known, not allowing accurate assessment of the star's location in the H-R diagram.

We undertook this study confident that modern detectors and analysis tools would improve this situation greatly. Two of the present authors (P. M. and N. M.) have contributed to this group of "poor" orbits; the designation is not a reflection of the effort put into such studies but rather of the difficulties in measuring very broad and weak lines using the only tools that were available 10 years ago: photographic emulsions and Grant oscilloscope measuring engines being then the state of the art. CCDs offer the possibility of obtaining high signal-to-noise ratio (SNR) observations at moderate dispersion, and even the simplest of digital analysis tool (such as the ability to fit both the lines of both components simultaneously) provides vast improvements over setting on line centers by eye. One of the most significant concerns we had about orbits in the literature—including our own—was the effect of pair blending. The lines in early-type stars are both broad and shallow, and despite the large masses resulting in large Doppler separations, line separations are often comparable to the individual line widths. In general, this should lead to a systematic underestimate of the radial velocity curve amplitude K. Since the masses go as K^3, even a 10% error in K will lead to a 30% error in the mass. (We note that the sum of two equal-depth and equal-width Gaussians, separated by only the FWHM of an individual line, will have apparent line centers that are 20% closer than the true separation, which would lead to a 60% error in the mass if no corrections are made.) We began our observations in 1991, and in the subsequent years excellent work on massive binaries have also been published by Harries, Hilditch, & Hill (1997), Hilditch, Harries, & Bell (1996), Hill & Holmgren (1995), Holmgren, Hill, & Scarfe (1995), Penny (1996); Penny, Gies, & Bagnuolo (1997), Stickland (1995, 1996), Stickland & Koch (1996), Stickland et al. (1992, 1994, 1996), Simon, Sturm, & Fiedler (1994), and Sturm & Simon (1994), among others. We were fortunate to have overlap with some of these modern studies, to provide confidence in our own work. In addition, new distances have been determined for many of the clusters and OB associations (Garmany & Stencel 1992;

Massey et al. 1995a). We combine these new orbits and distances with some of the more interesting older work to address the question of the mass discrepancy for massive stars.

1.1. *Selection of Systems*

We originally selected 23 systems from the Batten et al. (1989) *Eighth Catalog*, primarily based on the criterion that the system (*a*) contain main-sequence early-type stars (by "main-sequence" we mean H-burning, not necessarily luminosity class "V" objects); i.e., this restricted our study to systems with O and B type components and eliminated O + WR systems or VV Cep-like (OB + M I); (*b*) known to have double-lined spectra, (*c*) with minimum masses greater than 10 $M_\odot$; (*d*) north of $\delta \approx -30°$. Critical to our study was the requirement (*e*) that the stars have separations sufficiently large that the two stars are not interacting: we are, after all, interested in using the stellar masses from these binaries to resolve a controversy concerning the masses of *single* stars. Preference was then given to systems that (*f*) showed light-curve variations and hence either had a known orbital inclination or hopes of one being obtained in the future and (*g*) were a member of a cluster or OB association with a known (or determinable) distance. Some very interesting systems were dropped from our observing program because they proved too faint (HDE 228766 and V 729 Cyg; see Massey & Conti 1977 and Bohannan & Conti 1976); others we had undertaken believing that new, coudé dispersion, high-SNR data would dispel a mystery, only to find that this assumption was merely hubris. For instance, despite a wealth of new data on V 640 Mon ("Plaskett's Star"), we have made no progress in obtaining a useful orbit for the secondary component. We obtained complete data on 11 systems, seven of which yielded useful new orbit solutions. (We will describe the systems that did not work out in § 4.1.) We list the seven systems in Table 1, although we will find that not every system wound up meeting all of our stringent criteria—in particular, (*e*).

2. OBSERVATIONS, DATA REDUCTION, AND RADIAL VELOCITY MEASUREMENTS

The new spectra for this project were obtained during 56 nights between 1990 September and 1992 November plus two additional nights in 1996 July. All of the data were taken using the Coude Feed spectrograph at Kitt Peak National Observatory. Our original observing list contained 23 systems, and 395 spectra were obtained. All of the data were obtained with a 316 lines mm^{-1} grating ("B") in third order (blazed at 4000 Å) using Camera 5 for a reciprocal dispersion of 9.9 Å mm^{-1}. A Tektronix 1024^2 CCD ("T1KA") was used in 1990–1992 with 24 μm pixels and 240 Å coverage per setting. The resolution was 0.4 Å (0.23 Å pixel^{-1}). The observations in 1996 were made with a 15 μm Ford 1024 × 3072 CCD, with comparable resolution (albeit at 0.14 Å pixel^{-1}) but 440 Å coverage. For the 1990–1992 observations, we typically observed from 4450 to 4680 Å in order to include the He I λ4471, He II λ4542, Si III λ4553, N III $\lambda\lambda$4634, 4641, and C III λ4650 lines. In addition, we often observed with a second grating tilt (4000–4240 Å) in order to include the Si IV $\lambda\lambda$4089, 4116, Hδ, He I $\lambda\lambda$4023, He I λ4123, and He II λ4200 lines. All observations were made with a 4-96 blocking filter to eliminate both second-order red and fourth-order blue. The 1996 observations covered from 4180 to 4620 Å in one grating setting. A typical exposure time of 45 minutes at $B \approx 7$–7.5 resulted in an SNR of 500–600 per 0.4 Å spectral resolution element. A 250 μm (1″.8) slit was used throughout.

All the data were flat-fielded using a quartz lamp exposure illuminating the slit with the same f-ratio as the telescope beam, and wavelength calibration was provided by frequent exposures with a Th-Ar comparison source. Typical dispersion solution fits had RMS fits of 0.005 Å. The spectra were extracted using an optimal extraction algorithm and wavelength calibrated using IRAF routines.

Owing to the fact that many of these systems have well-known ephemerides, it was possible to plan the observations so that spectra were taken at double-lined phases. In some cases the published orbits were old enough and/or the periods not of sufficient accuracy to span the gap to the present epoch, and additional observations were needed.

Once we reduced the data, we measured the wavelengths of the centers of readily apparent double lines in the spectra using the routine IRAF's "splot" interactive spectral analysis program. Rather than attempt any cross-correlation method (which traditionally has been used on all spectral lines in a given region, regardless of their suitability), we instead used the relatively simple method of simultaneously fitting two Gaussians to the best double lines in each spectrum. We find that although the effects of line blending become of decreased significance at large velocity separations (>300 km s^{-1}), we still notice differences of 0.2 Å between the apparent line centers and those determined by our deblending technique. We relied primarily on the strongest non-Balmer lines, particularly the He I lines at 4026, 4143, and 4471, and the He II lines at 4200

TABLE 1

SYSTEMS WITH NEW ORBIT SOLUTIONS

System	Spectral Type (New)	Distance Modulus: Value (mag)	Distance Modulus: Basis	Inclination: Value	Inclination: Reference
V453 Cyg	B0.7 III + B1 V	11.65 ± 0.07	NGC 6871	86°.4 ± 1°.0	1, 2
HD 191201......	O9.5 V–III + O9.5 V–III	11.65 ± 0.07	NGC 6871	Unknown	...
V382 Cyg	O6.5 V((f)) + O6 V((f))	11.5 ± 0.3	Cyg OB1	84°.5 ± 0°.1	3
Y Cyg...........	O9 V + O9.5 V	11.5 ± 0.5	Spectroscopic parallax	86°.7 ± 0°.5	4
HD 206267......	O6.5 V((f)) + O9.5: V	9.9 ± 0.3	Tr 37	Unknown	...
DH Cep	O5.5 III(f) + O6 III(f)	12.85 ± 0.10	NGC 7380	47°.1 ± 1°.0	5
AH Cep	B0.2 V + B2 V	9.1 ± 0.6	Spectroscopic parallax	69°.2 ± 12°.0	6

REFERENCES.—(1) Cohen 1974. (2) Wachmann 1974. (3) Harries et al. 1997. (4) Hill & Holmgren 1995. (5) Hilditch et al. 1996. (6) Bell et al. 1986.

and 4542 Å. These lines were relatively strong and had the cleanest double-line behavior. Typically, only one or two clearly double lines could be measured on each spectrogram.

We averaged the heliocentric radial velocities for all lines on a single spectrogram for both the primary and secondary components. (We refer to the "primary" as the star of greater line strength; since the spectral types are similar in each system, this should be the visually brighter member and also the more luminous and massive component.) The heliocentric JD (corrected to midexposure), orbital phase (computed as described in the next section), heliocentric radial velocities for the primary and secondary, the differences between observed radial velocities and those calculated from the orbit solution, and assigned weights for the radial velocities (usually the square-root of the number of lines measured) are listed in Table 2 (which will be published in its entirely in the AAS CD-ROM Series, Vol. 9).

3. ORBIT RESULTS

We used a FORTRAN program that performed differential corrections to minimize orbital residuals. We list the adopted orbital parameters in Table 3 and show the orbit solutions in Figure 1. In all cases we began by adopting the periods from the literature, although in a few cases we were able to revise the periods slightly using our latter-epoch data. To avoid confusion we explicitly note that for the noncircular orbits the time T refers to the time of periastron passage, while for the circular orbits T corresponds to maximum radial velocity of the primary. For orbit solutions whose initial solutions indicated eccentricities that were zero to within the uncertainties, we adopted circular orbits and solved for each component's orbit separately. In principle there could be a phase difference in the solutions, but in practice there was always very good agreement between the T's for the two components, and we list only the single values in Table 3. For the noncircular orbits, we first solved for the primary's orbital elements. Then, in order to obtain the best possible solutions for the semiamplitude of the secondary, we fixed e, ω, and T and solved only for the γ-velocity and the semiamplitude K_s. (We allowed γ to vary, as stellar winds can result in the two components having slightly different γ velocities; failing to allow for this can result in spurious values for K; see discussion in Massey & Conti 1977).

TABLE 2

RADIAL VELOCITIES

		Primary			Secondary		
HJD 2,400,000+	Phase	V_r (km s^{-1})	$O-C$ (km s^{-1})	Weight	V_r (km s^{-1})	$O-C$ (km s^{-1})	Weight
			V453 Cyg				
48141.789	0.99	159	4.5	1.4	−219	8.3	1.4
48141.840	0.00	153	−2.2	1.0	−213	13.7	1.0
48143.754	0.50	−196	−5.0	1.0	199	−0.5	1.0
48143.812	0.51	−180	11.5	1.4	200	3.0	1.4
48145.609	0.97	158	6.1	1.4	−228	−0.6	1.4
48145.656	0.98	149	−5.2	1.0	−219	8.8	1.0
48195.676	0.84	77	−0.9	1.4	−156	−7.0	1.4
48195.730	0.86	84	−6.2	1.0	−167	−4.1	1.0
48431.805	0.55	−185	−1.3	1.0	189	6.1	1.0
48433.660	0.03	150	−2.4	1.0	−208	13.2	1.0
48519.598	0.12	102	−6.7	1.4	−165	−7.1	1.4
48519.645	0.13	105	5.3	1.0	−151	−6.2	1.0
48522.773	0.93	137	−3.2	1.0	−214	3.3	1.0
48522.820	0.95	152	6.2	1.4	−224	−2.9	1.4
48583.691	0.60	−162	−1.4	1.0	167	16.8	1.0
48585.582	0.08	134	1.7	1.0	−197	−7.4	1.0
48785.727	0.54	−186	1.6	1.0	183	−6.4	1.0
48786.754	0.80	37	2.4	1.0	−134	−36.8	1.0
48787.688	0.04	149	−0.5	1.0	−211	4.8	1.0
48882.824	0.50	−194	−2.9	1.0	203	3.7	1.0
48884.766	1.00	153	−1.7	1.0	−218	9.8	1.0
48886.621	0.47	−196	−7.0	1.0	200	0.6	1.0
48946.566	0.88	112	0.7	1.0	−187	−1.5	1.0
48947.602	0.15	86	2.5	1.0	−147	−23.7	1.0
48950.684	0.94	140	−4.2	1.0	−205	14.8	1.0
			HD 191201				
48141.883	0.08	146	10.1	1.4	−199	−40.9	1.4
48195.625	0.53	−118	1.5	1.4	125	−24.6	1.4
48195.652	0.54	−117	1.7	1.4	109	−39.8	1.4
48433.941	0.13	110	−3.4	1.4	−106	27.2	1.4
48582.668	0.97	158	4.6	1.4	−196	−25.0	1.4
48787.730	0.58	−93	13.3	1.0	141	4.2	1.0
48788.691	0.69	−46	−12.5	1.4	131	76.3	1.0
48950.715	0.13	101	−8.6	1.4	−109	19.9	1.4
50277.812	0.37	−79	−2.9	1.4	115	25.8	1.4

NOTE.—Table 2 is published in its entirety in computer-readable form in the AAS CD-ROM Series, Vol. 9.

TABLE 3

ORBITAL ELEMENTS

A. CIRCULAR ELEMENTS

	V453 Cyg		HD 191201		V382 Cyg		DH Cep		AH Cep	
PARAMETER	Primary	Secondary	Primary	Secondary	Primary	Secondary	Primary	Secondary	Primary	Secondary
Spectral type	B0.7 III	B1 V	O9.5 V–III	O9.5 V–III	O6.5 V((f))	O6 V((f))	O5.5 III(f)	O6 III(f)	B0.2 V	B2 V
Δm	0.75 ± 0.1		0.6 ± 0.1		0.4 ± 0.1		0.25 ± 0.1		0.25 ± 0.1	
Period (days)	3.8898128		8.3343		1.885512		2.110912		1.774761	
T (HJD − 2,400,000)	48141.82 ± 0.01		48141.15 ± 0.06		48432.87 ± 0.02		48143.64 ± 0.01		48198.43 ± 0.01	
K (km s^{-1})	173.2 ± 1.3	213.6 ± 3.0	138.8 ± 4.3	163.3 ± 17.9	256.4 ± 6.4	375.1 ± 6.2	224.9 ± 4.2	261.3 ± 3.7	230.0 ± 3.2	277.6 ± 4.4
γ (km s^{-1})	-18.2 ± 1.1	-14.1 ± 2.7	16.3 ± 3.1	-12.3 ± 15.0	-3.8 ± 6.0	-0.1 ± 5.9	-33.4 ± 3.2	-33.4 ± 2.9	-23.2 ± 1.9	-17.9 ± 2.8
σ_{fit} (km s^{-1})	3.6	8.4	7.3	33.3	14.7	14.4	9.2	8.2	7.0	10.3
$m \sin^3 i$ ($M_\odot$)	12.9 ± 0.4	10.5 ± 0.2	12.9 ± 2.9	11.0 ± 0.9	29.3 ± 1.1	20.0 ± 0.9	13.5 ± 0.4	11.7 ± 0.4	13.2 ± 0.4	10.9 ± 0.3
$a \sin i$ ($R_\odot$)	13.3 ± 0.1	16.4 ± 0.2	22.8 ± 0.7	26.9 ± 3.0	9.6 ± 0.2	14.0 ± 0.2	9.4 ± 0.2	10.9 ± 0.2	8.1 ± 0.1	9.7 ± 0.2

B. NONCIRCULAR ELEMENTS

	Y Cyg		HD 206267	
PARAMETER	Primary	Secondary	Primary	Secondary
Spectral Type	O9 V	O9.5 V	O6.5 V((f))	O9.5: V
Δm	0.2 ± 0.1		1.2 ± 0.1	
Period (days)	2.9963328		3.709838	
e	0.176 ± 0.013		(0.119)	
ω (deg)	350.0 ± 4.6		(13.1)	
T (JD − 2,400,000)	48418.39 ± 0.03		(49239.72)	
K (km s^{-1})	250.4 ± 2.4	236.9 ± 3.7	187.5 ± 5.7	307.6 ± 3.8
γ (km s^{-1})	-66.6 ± 2.8	-64.0 ± 4.7	-10.7 ± 9.4	-6.8 ± 8.3
σ_{fit} (km s^{-1})	8.2	15.3	17.3	9.5
$m \sin^3 i$ ($M_\odot$)	16.7 ± 0.5	17.6 ± 0.4	28.4 ± 1.5	17.3 ± 1.5
$a \sin i$ ($R_\odot$)	14.6 ± 0.1	13.8 ± 0.2	13.6 ± 0.4	22.4 ± 0.3

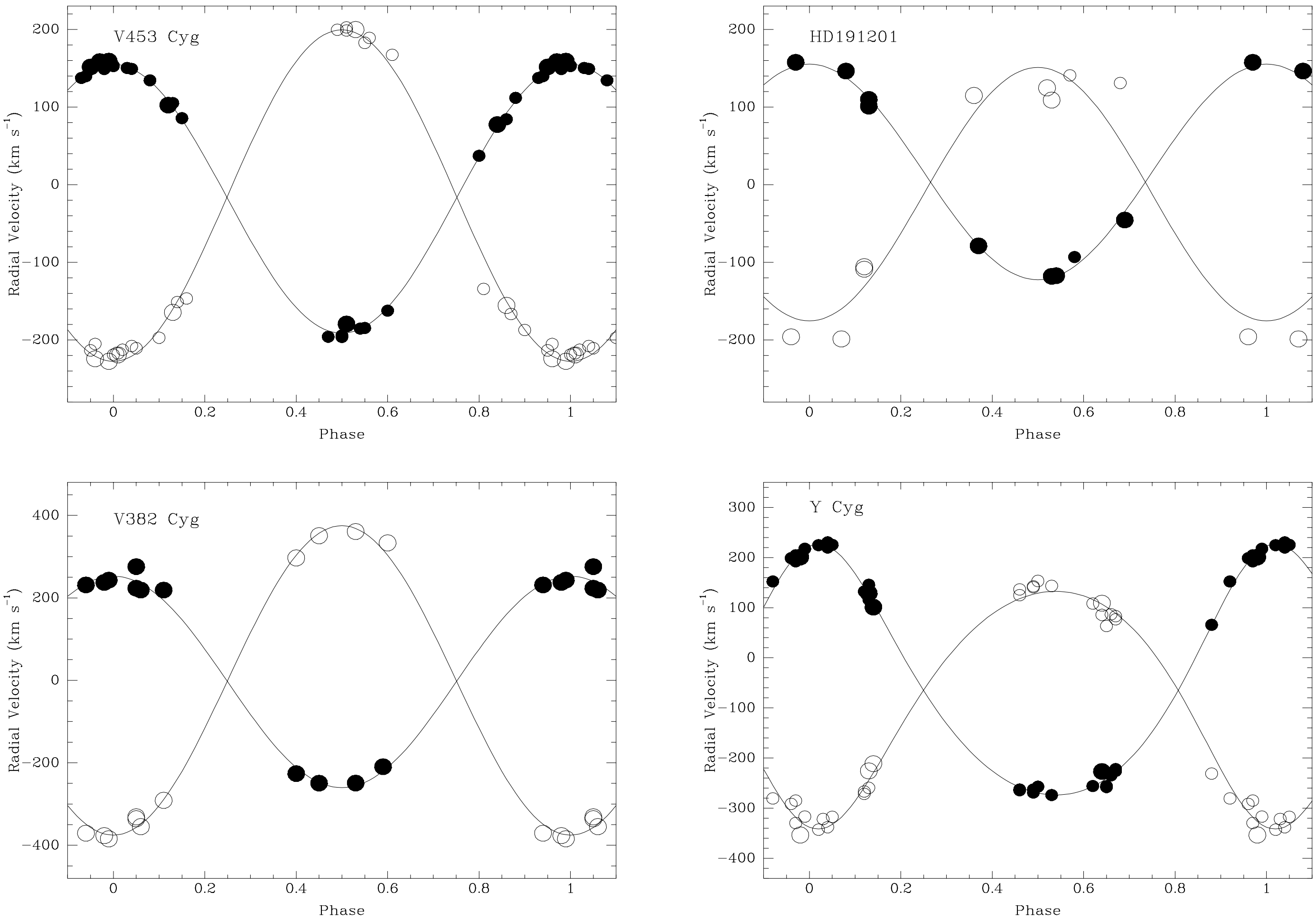

FIG. 1.—New orbit solutions for our seven systems. The heliocentric radial velocities of the primary are shown by filled circles; those of the secondary are shown by open circles. The size of the symbol is proportional to the weight assigned in the orbit solution.

It is crucial for our purposes to obtain both good spectral classifications for each star and to determine the fractional light contributed by each component (at what is essentially B). This information will be combined with the photometry and distances (when known, or with spectroscopic parallaxes when it is not) in the next section for determining the luminosity of the components. We classified the stars using the best double-lined spectrograms and using the precepts of the Walborn & Fitzpatrick (1990) spectral atlas of O and B stars. We measured the magnitude difference between the two components using the classification lines if the stars were of identical type, deferring to the Balmer hydrogen lines in the case they were not. (The lines were measured at both quadratures and the results averaged, although no obvious differences were apparent between the two.) We list the adopted spectral types and magnitude differences in Table 3 as well.

The double-lined orbit results produce values of the minimum masses $m_p \times \sin^3 i$ and $m_s \times \sin^3 i$. To obtain the actual masses, we need to know the inclination i. As described in § 1.1, we used as one of our criteria that the star have partial eclipses or ellipsoidal light variations and, hence, either have a known inclination or one that can be readily found in the future. We include in our discussions the source of the inclinations; these are also summarized in Table 1.

Finally, in order to compute luminosities, we need to know the reddening and distance to each system. Again, membership in a cluster or association was one of the criteria we used for including a star in our observing program (§ 1.1), although we did not insist on it. In the cases where no such distance is known, we can adopt a distance based on the M_V corresponding to the star's spectral classification using the calibration of Conti (1988) for the O-type stars and Humphreys & McElroy (1984) for the B-type stars. The intrinsic colors of FitzGerald (1970) as a function of spectral type were assumed. We include in Table 1 the adopted distances, along with their uncertainties, as these play a major role in determining the errors in our comparison with stellar evolution models in § 4.

Here we briefly summarize our results, and compare them to previous values found in the literature.

3.1. *Discussion of Individual Systems*

3.1.1. *V453 Cyg = HDE 227696 = B1203*

Pearce (1941) found $K_p = 181.8$ km s^{-1} and $K_s = 237.4$ km s^{-1}. Abt, Levy, & Gandet (1972) found a considerably smaller value of K_p, 152 km s^{-1}, although Batten et al. (1989) note that the Abt et al. result is based on fewer data, and Popper (1978) cited good agreement with Pearce's result. Our semiamplitudes ($K_p = 173.2 \pm 1.3$ km s^{-1} and

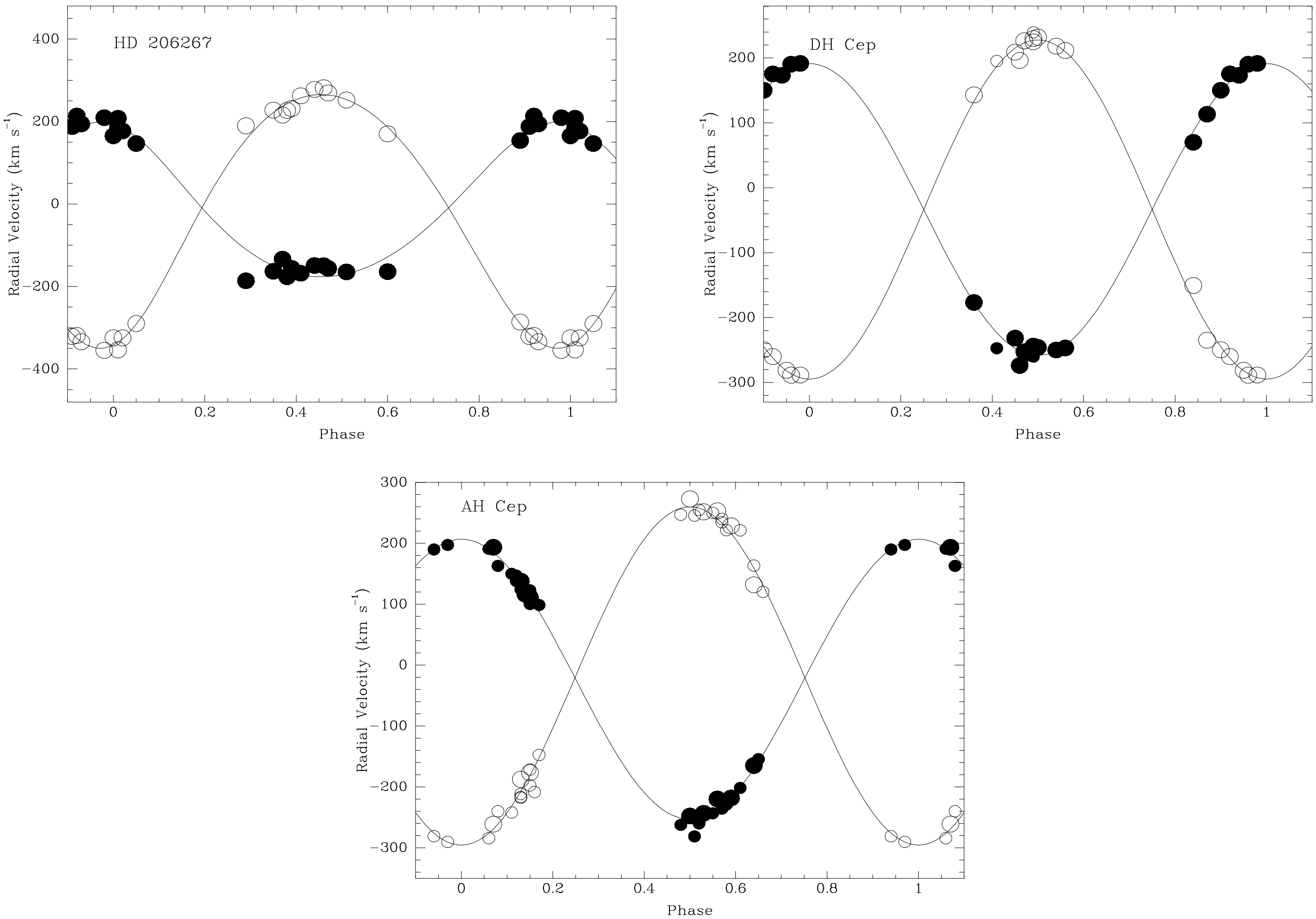

FIG. 1—*Continued*

$K_s = 213.6 \pm 3.0$ km s^{-1}) are well determined and are intermediate between the values of Abt et al. and Pearce.

Cohen (1968, 1974) and Wachmann (1974) discuss the photometry of this system. Wachmann finds $i = 85.°8 \pm 1°$, while Cohen derives a nearly identical result ($i = 86.4°$). We adopt $i = 86.°4 \pm 1°$.

Our spectral types of B0.7 III and B1 V are consistent both with the values B0.5 IV and B0.5 IV found by Pearce (1941) and with membership in the cluster NGC 6871. The magnitude difference between the two components is large (we estimate $\Delta m = 0.75 \pm 0.1$), again, consistent with the primary being of slightly greater luminosity. The photometry ($V = 8.31$ and $B-V = 0.18$) combined with the spectral types leads to a value of $E(B-V) = 0.44$, in good agreement with the average value $E(B-V) = 0.46$ found for NGC 6871 by Massey et al. (1995a). With a distance modulus of 11.65, we compute $M_V = -4.3 \pm 0.2$ and $M_V = -3.5 \pm 0.3$, in excellent agreement with the M_V calibration for the spectral types and with the values of -4.1 and -3.2 derived by Wachmann (1974) in his analysis of the light curve.

3.1.2. *HD 191201 = B1206*

This star was first analyzed by Plaskett (1926), which was also the last spectroscopic study until the present time. Plaskett derived $K_p = 157.0$ km s^{-1} and $K_s = 168.5$ km s^{-1}, although Batten et al. (1989) note that the "value of [K_s], and therefore the total mass of the system, must be considered as very poorly determined." Nevertheless, our values of $K_p = 138.8 \pm 4.3$ km s^{-1} and $K_s = 163.3 \pm 17.9$ km s^{-1} are in reasonably good agreement, despite the large scatter in the orbit solution for the secondary. We have good phase coverage, although fewer data than we would like.

We find spectral types of O9.5 V for both components, and a magnitude difference of 0.6 ± 0.1, similar to the value 0.5 found by Plaskett (1926).

The star is a member of NGC 6871, and combining the photometry with the spectral types lead to a color excess of $E(B-V) = 0.43$, in excellent agreement with the average value of reddening for the cluster $E(B-V) = 0.46 \pm 0.03$ found by Massey et al. (1995a). The distance modulus of 11.65 ± 0.07 found by Massey et al. leads to slightly more luminous values for M_V than would be expected for the spectral types, evidence that the stars are slightly evolved.

Unfortunately, there is no good evidence on the orbital inclination. Zakirov (1992) has suggested a value of near 75°, but this seems highly implausible given the small minimum masses the orbit solution yields and the early spectral types.

3.1.3. *V382 Cyg = HD 228854 = B1222*

Pearce (1952) derived values of $K_p = 331.7$ km s^{-1} and $K_s = 378.4$ km s^{-1}, although Popper (1978) felt that these values were too large. Our analysis finds values of $K_p = 256.5 \pm 6.4$ km s^{-1} and $K_s = 375.1 \pm 6.2$ km s^{-1}; the semiamplitude of the secondary is in good agreement with that found by Pearce, but our semiamplitude of the primary is considerably smaller than what he found. The system has just been analyzed by Harries et al. (1997), who find $K_p = 260.2 \pm 2.8$ km s^{-1} and $K_s = 350.8 \pm 3.8$ km s^{-1}; thus, our primary is good agreement with Harries et al., but our secondary has a somewhat larger semiamplitude. Harries et al. used cross-correlation techniques to measure their radial velocities and then applied a correction for pair blending. Despite the fact that we have fewer points in our velocity curve than Harries et al., we prefer our orbit solution, since pair blending is explicitly accounted for in the measuring procedure and as we have better phase coverage around quadrature.

Harries et al. (1997) derive an inclination of $84.5° \pm 0.1°$ from their light-curve analysis, which we adopt. Landolt (1975) has also provided *UBV* data, although he does not quote an actual value for the inclination.

Our spectral classifications are O6.5 V((f)) and O6 V((f)) for the two components. These agree well with the O6/O7 classification adopted by Harries et al. (1997) and are similar to the "O7.3" and "O7.7" types given by Popper (1980), although clearly his interpolated spectral types cannot be taken literally. Koch, Siah, & Fanelli (1979) derive O6–O7 spectral type based on the UV continuum distribution.

We find a magnitude difference of $\Delta m = 0.4 \pm 0.1$ mag, which combined with the spectral types and photometry ($V = 8.93$ and $B-V = 0.70$) suggests a color excess $E(B-V) = 1.02$. The star is listed by Garmany & Stencel (1992) as a member of Cyg OB1, although it is clear from Massey et al. (1995a) that NGC 6913 and Berkeley 86 (both clusters that are included in Cyg OB1) are at slightly different distances. We adopt an intermediate distance modulus of 11.5 ± 0.3, where the large error reflects the uncertainty as to which (if either) subgroup this star belongs.

3.1.4. *Y Cyg = HD 198846 = B1266*

Excellent modern studies have been carried out for this system. Stickland et al. (1992) use *IUE* data and cross-correlations to derive velocity curves for the two components, finding $K_p = 242.2 \pm 2.5$ km s^{-1} and $K_s = 237.0 \pm 1.7$ km s^{-1}, while Hill & Holmgren (1995) find $K_p = 242.1 \pm 1.7$ km s^{-1} and $K_s = 244.0 \pm 2.4$ km s^{-1}. Simon, Sturm, & Fiedler (1994) make use of their "disentangling" method to calculate $K_p = 238.9 \pm 0.5$ km s^{-1} and $K_s = 246.4 \pm 0.5$ km s^{-1}. Our values, $K_p = 250.4 \pm 2.4$ km s^{-1} and $K_s = 236.9 \pm 3.7$, are consistent with these. We note that the star that we find to be slightly brighter (the magnitude difference between the two components is small) is actually the one with the larger orbital semiamplitude and smaller mass.

We derive spectral types of O9 V and O9.5 V for the two components and find a magnitude difference of 0.2 ± 0.1. The spectral types and the photometry ($V = 7.29$, $B-V = -0.06$) suggest a color excess of $E(B-V) = 0.25$.

The orbital inclination was found by Hill & Holmgren (1995) to be $86\overset{\circ}{.}7 \pm 0\overset{\circ}{.}5$.

Unfortunately, Y Cyg is not a member of any cluster or OB association. (Its large systemic velocity suggests it is a runaway star; see Gies & Bolton 1986.) We adopt a spectroscopic distance modulus of 11.5 ± 0.5 mag, based on adopting $M_V = -4.4$ for an O9 V star and $M_V = -4.0$ for an O9.5 V star (Conti 1988).

3.1.5. *HD 206267 = B1321*

Stickland (1995) solved the riddle of this system by determining that it was a triple; what others had assumed was the spectrum of the secondary was actually that of a third body with constant radial velocity. The real secondary showed up only as a very weak peak in the cross-correlations of his *IUE* data. Based on his description, we were ready to wash our hands of the system when we noticed that not only could we resolve all three components in our spectra, but we could also measure all the lines using triple Gaussian fits. We adopted Stickland's period, eccentricity, and ω based on his very nice phase coverage of the motion of the primary and then used our data to determine γ and the orbital semiamplitudes. We found $K_p = 187.5 \pm 5.7$ km s^{-1} and $K_s = 307.6 \pm 3.8$ km s^{-1}, compared with Stickland's $K_p = 161.1 \pm 2.7$ km s^{-1} and $K_s = 288.0 \pm 11.5$ km s^{-1}. Our larger values are again indicative of pair blending's insidious effects. We note that allowing e to be a free parameter in our solutions resulted in inconsistent values of e and ω between the primary and secondary (due, doubtless, to the difficulties in obtaining good radial velocities for three blended lines), but nearly identical values of the semiamplitudes.

We note that of the early efforts to measure its radial velocity curve, only Crampton & Redman (1975) attempted to measure the secondary, and these earlier efforts were are all dubious given the unrecognized presence of the third body. The velocity of the third body is -14.6 ± 7.5 km s^{-1}, similar to the γ velocities, suggesting that this is either a distant third member of the system or a fellow traveler.

The spectral types are O6.5 V((f)) and O9.5: V, with the latter somewhat uncertain due to the faintness of its features despite our high signal-to-noise data. The magnitude difference is 1.2 ± 0.3. The third body is intermediate in brightness and also appears to be of OB type.

Crampton & Redman (1975) note that there is some evidence of light variability, although no light curve has been obtained or analyzed; thus, there is no inclination known for this interesting system, and we will be able to use only the minimum masses in our analysis.

The star is a member of Tr 37 in Cep OB2; we adopt a distance modulus of 9.9 ± 0.3 from Garmany & Stencil (1992). The combination of spectral types and photometry ($V = 5.62$ and $B-V = 0.21$) leads to a color excess $E(B-V) = 0.51$.

3.1.6. *DH Cep = HD 215835 = B1399*

Modern studies of DH Cep include Sturm & Simon (1994), Hilditch et al. (1996), and most recently Penny (1996) and Penny et al. (1997). Sturm & Simon list semiamplitudes of $K_p = 213 \pm 6$ km s^{-1} and $K_s = 249 \pm 6$ km s^{-1}, based on their "disentangling" method; however, combining their radial velocity data with ours, we find good agreement with the semiamplitudes that we obtain from our data alone: $K_p = 224.9 \pm 4.2$ and $K_s = 261.3 \pm 3.7$. Hilditch et al. list semiamplitudes of $K_p = 229.6 \pm 2.6$ km s^{-1} and $K_s = 251.7 \pm 2.7$ km s^{-1}, also in reasonable agreement with ours. The use of a slightly longer period by Hilditch et al. does not appear justified by our data; we find that a slightly shorter period (2.1108219 days) is consistent with all the data sets. Penny et al. derive $K_p = 223 \pm 7$ km s^{-1} and $K_s = 247 \pm 10$ km s^{-1}, again in reasonable agreement with ours. In all cases our value for the semiamplitude of the secondary is larger, which we again attribute to our having explicitly removed the effects of pair blending.

We classify the stars as O5.5 III(f) and O6 III(f), similar to Walborn's (1973) *composite* type of O6 V((n)) and Penny's (1996) tomographic decomposition of O6 V and O7 V. The luminosity class "III" for the two components is consistent with the N III emission and weakness of He II $\lambda4686$, although we could have chosen a "V((f))" luminosity classification for the two components. The "III(f)" classification, however, is also suggested by the absolute magnitude implied by its membership in NGC 7380, with a distance modulus of 12.86 ± 0.10 (Massey et al. 1995a).

We compute a magnitude difference between the two components of 0.25 ± 0.1 mag. This agrees well with the flux ratio found by Penny (1996). Based on the spectral types and photometry ($V = 8.58$ and $B-V = 0.34$), we then derive $E(B-V) = 0.65$, in excellent accord with the average cluster reddening $E(B-V) = 0.64 \pm 0.03$ found by Massey et al. (1995a) for NGC 7380.

We adopt the orbital inclination $i = 47° \pm 1°$ found by Hilditch et al. (1996). Penny et al. (1997) argue that the range in acceptable (if not necessarily optimum) inclinations could be much greater than that, although we note that Sturm & Simon (1994) independently find $i = 47° \pm 1°$.

3.1.7. *AH Cep = HD 216014 = B1401*

Speculation exists in the literature that a third body may be present in the AH Cep system based on the light-curve analysis of Drechsel, Lorenz, & Mayer (1989), although none has been detected spectroscopically. Bell, Hilditch, & Adamson (1986) find $K_p = 249 \pm 8$ km s^{-1} and $K_s = 283 \pm 8$ km s^{-1}, although Batten et al. (1989) note that the value of K_s is perhaps more uncertain than the formal error would indicate. Holmgren, Hill, & Fisher (1990) obtained new spectra, which they measured via cross-correlation to yield significantly smaller semiamplitudes ($K_p = 237 \pm 2$ km s^{-1} and $K_s = 269 \pm 2$ km s^{-1}). We find semiamplitudes of $K_p = 230.0 \pm 3.2$ and $K_s = 277.6 \pm 4.4$ km s^{-1}.

We derive spectral types of B0.2 V and B2 V for the two components, similar to the B0.5 V and B2 V types given by Holmgren et al. (1990). We measure a magnitude difference of 0.25 ± 0.10 between the two components, essentially identical to the $\Delta B = 0.28 \pm 0.08$ value found by Holmgren et al. We adopt the orbital inclination $i = 69\overset{\circ}{.}2 \pm 12°$ found by Bell, Hilditch, & Adamson (1986).

Unfortunately, AH Cep is not a member of any cluster or association. The spectral types and photometry ($V = 6.92$ and $B-V = 0.27$) suggest a color excess of $E(B-V) = 0.54$ and $A_V = 1.67 \pm 0.06$. The spectral classifications would then lead to a distance modulus of 9.1 ± 0.6, coincidentally identical to the value found by Holmgren et al. (their Table 1) using different photometry and the measured equivalent width of Hγ.

3.2. *Systems That Proved Intractable*

Although the above seven systems listed above are not necessarily ideal, they did not present the difficulties found in the following five systems, briefly described below.

EO Aur = HD 34333 = B308.—First analyzed by Pearce (1943), this system has very difficult to resolve double lines (Popper 1978). Although our radial velocity curve for the primary is well defined, our secondary curve was not deemed acceptable. The broadness of the lines in the secondary causes us to speculate that this system is affected by a third body, as most of the other stars in this section are.

IU Aur = HD 35652 = B322.—We were not able to achieve good orbits for either the primary or secondary, which we attribute to the presence of a third body (see discussion in Batten et al. 1989 and references therein). In addition, according to Drechsel et al. (1994), the system appears to be semidetached.

V640 Mon = HD 47129 = B411.—Otherwise known as Plaskett's star, this system has received a great deal of attention because it appears to contain the most massive binary component, rumored at 60 + $M_\odot$. Naturally, we were very interested in this system and were disappointed to encounter the same difficulties in measuring the secondary as faced by everyone else, most recently Stickland (1987), Bagnuolo, Gies, & Wiggs (1992), Underhill (1993), and Bagnuolo & Barry (1996). The latter may have detected the secondary in the optical via tomographic analysis. (See also Stickland 1997.) This is a case where extremely high signal-to-noise data coupled with high dispersion made little improvement over the difficulties first encountered by Plaskett (1922).

LY Aur = HD 35921 = B325.—This system has received much attention by such authors as Stickland et al. (1994), Popper (1982), and Drechsel et al. (1989). All three agree on the third-body light contribution that blends with the eclipsing components making the determination of accurate radial velocities nearly impossible. Although our secondary radial velocity curve was well-defined, we too found a large scatter in the primary radial velocity curve, consistent with these other studies. Unlike the case of HD 206267, it was not possible on most of our images to visually determine the line contribution from the third body. However, our velocity curve for the secondary agreed well with the results given by Stickland et al. (1994).

29 UW CMa = HD 57060 = B443.—We were attracted to this system as both components are early, and the secondary has never had a well-determined orbit solution despite attempts by numerous pundits—see the discussion in Batten et al. (1989) and the excellent review of the early literature given by Stickland (1989): both Pearce (1932) and Struve et al. (1958) felt they had detected the secondary, but the two disagreed strongly in its radial velocity curve. Our data gave a well-defined primary solution but very large scatter for the secondary. Stickland (1989) was unable to detect the secondary. Although Bagnuolo et al. (1994) used tomographical analysis and indirect methods to argue that the mass ratio had to be $\approx 1.16 \pm 0.16$ (secondary more massive), no actual radial velocity curve for the secondary was found. (See also Stickland 1997.) We conclude that this, too, is a system where better data simply are not sufficient to provide a good orbit.

4. MASSES, LUMINOSITIES, AND COMPARISON WITH MODELS

We are now ready to do what we set out in the introduction, to answer how well the binary masses agree with the stellar evolutionary models. We list in Table 4 the derived parameters that we will use as input to the stellar evolutionary models and an estimate of their errors; we have computed M_{bol} using the data given above, applying the spectral type to effective temperature and bolometric corrections calibrations of Chlebowski & Garmany (1991) for the O-type stars and Humphreys & McElroy (1984) for the B-type stars. The errors on the individual M_{bol} values

TABLE 4

ADOPTED AND DERIVED QUANTITIES

	Adopted Spectral Type			−1 Subtype			+1 Subtype		
Star	log T_{eff}	M_{bol}	R_* ($R_\odot$)	log T_{eff}	M_{bol}	R_* ($R_\odot$)	log T_{eff}	M_{bol}	R_* ($R_\odot$)
V453 Cyg:									
B0.7 III	4.324	−6.5 ± 0.2	13.1 ± 1.2	4.481	−7.5 ± 0.2	10.3 ± 0.9	4.301	−6.2 ± 0.2	12.9 ± 1.2
B1 V	4.307	−6.0 ± 0.3	11.5 ± 1.6	4.471	−6.6 ± 0.3	7.1 ± 1.0	4.294	−5.5 ± 0.3	9.7 ± 1.3
HD 191201:									
O9.5 V–III......	4.530	−8.5 ± 0.2	13.0 ± 1.3	4.539	−8.6 ± 0.2	13.1 ± 1.2	4.476	−8.2 ± 0.2	14.5 ± 1.3
O9.5 V–III......	4.530	−7.9 ± 0.2	9.9 ± 0.9	4.539	−8.0 ± 0.2	9.9 ± 0.9	4.476	−7.6 ± 0.2	11.0 ± 1.0
V382 Cyg:									
O6.5 V((f))	4.615	−9.0 ± 0.4	11.1 ± 2.0	4.625	−9.1 ± 0.4	11.1 ± 2.0	4.603	−8.9 ± 0.4	11.2 ± 2.1
O6 V((f))	4.625	−8.7 ± 0.4	9.2 ± 1.7	4.635	−8.7 ± 0.4	8.8 ± 1.6	4.615	−8.6 ± 0.4	9.2 ± 1.7
Y Cyg:									
O9 V	4.555	−7.8 ± 0.7	8.4 ± 2.8	4.568	−7.9 ± 0.7	8.3 ± 2.7	4.543	−7.7 ± 0.7	8.5 ± 2.8
O9.5 V	4.543	−7.5 ± 0.7	7.7 ± 2.5	4.555	−7.6 ± 0.7	7.7 ± 2.5	4.471	−7.1 ± 0.7	9.0 ± 2.9
HD 206267:									
O6.5 V((f))	4.615	−9.5 ± 0.4	13.9 ± 2.6	4.625	−9.6 ± 0.4	13.9 ± 2.6	4.592	−9.3 ± 0.4	14.1 ± 2.6
O9.5: V	4.543	−7.8 ± 0.4	8.9 ± 1.6	4.555	−7.9 ± 0.4	8.8 ± 1.6	4.471	−7.4 ± 0.4	10.3 ± 1.9
DH Cep:									
O5.5 III(f)	4.616	−9.5 ± 0.2	13.9 ± 1.3	4.646	−9.7 ± 0.2	13.2 ± 1.2	4.604	−9.5 ± 0.2	14.7 ± 1.4
O6 III(f)	4.604	−9.3 ± 0.2	13.4 ± 1.2	4.635	−9.4 ± 0.2	12.1 ± 1.1	4.593	−9.2 ± 0.2	13.4 ± 1.2
AH Cep:									
B0.2 V	4.449	−6.0 ± 1.0	6.0 ± 2.8	4.471	−6.1 ± 1.0	5.6 ± 2.7	4.383	−5.6 ± 1.0	6.7 ± 3.2
B2 V	4.294	−4.8 ± 1.0	7.0 ± 3.3	4.338	−5.0 ± 1.0	6.3 ± 3.0	4.283	−4.7 ± 1.0	7.0 ± 3.4

include only the errors in the distances and magnitude differences; these are clearly largest for the systems without cluster memberships. However, if we also allow for errors of one spectral subtype (which is certainly possible), then there will also be a resulting errors in M_{bol} and stellar radii (R_*), which we list as well. Uncertainties in the effective temperature scale for hot stars are small compared with these errors; compare, for example, Vacca, Garmany, & Shull (1996) with Chlebowski & Garmany (1991) and Humphreys & McElroy (1984).

Before we make a comparison between our derived masses and those determined from evolutionary tracks, it is useful to examine one remaining question: are these systems really fully detached? We noted in § 1.1 that we were only interested in systems which were noninteracting, as we are, after all, trying to use these masses to understand the situation in regard to single stars. We can approximate the Roche lobe radius of star "1," R_{L_1}, by

$$R_{L_1} \sin i = (a_p + a_s) \sin i \times \left(0.38 + 0.2 \log \frac{m_1}{m_2}\right)$$

according to Paczynski (1970). We list these values in Table 5, using the inclinations from Table 1 and the orbital solutions from Table 3, and compare these with the stellar radii R_* from Table 4. (It should be remembered that these values are not determined by *assuming* some radius for the luminosity classes; instead, the luminosity class enters only in what temperature we adopt for the stars.) We find that most of our systems are likely detached; the exceptions are V382 Cyg and DH Cep, the components of which are likely near their Roche lobes. Harries et al. (1997) and Penny (1996) reach the same conclusion, respectively, for these two systems. (See also Penny et al. 1997.)

Although we talk about the "mass-luminosity" relationship, the stars that we are describing (those that occupy the upper left of the H-R diagram) evolve on a timescale of a few million years, and this evolution proceeds neither at constant luminosity nor at constant mass, due to the effects of mass loss. Therefore, we compare our results to those of the evolutionary models of Schaller et al. (1992) by using the location of a star in the H-R diagram (log T_{eff} and M_{bol}) and comparing the masses derived from our binary solutions with the mass expected for a star occupying the same location in the H-R diagram from the evolutionary models. This comparison is given in Table 6 and is shown graphically in Figure 2. The range of masses listed for the models in Table 6 include both the uncertainties in M_{bol} for the adopted spectral type and the error introduced by an uncertainty of one spectral subtype. Note that these models explicitly include mass loss, and the range of model masses given in Table 6 include this, although typically this amounts to no more than a single solar mass.

TABLE 5

TEST FOR DETACHMENT

Star	R_* ($R_\odot$)	R_L ($R_\odot$)	Detached?
V453 Cyg:			
B0.7 III	9.4–14.3	12	Possible
B1 V	6.1–13.1	11	Probable
HD 191201:			
O9.5 V–III......	12.0–15.8	>20	Definite
O9.5 V–III......	9.0–12.0	>18	Definite
V382 Cyg:			
O6.5 V((f))	9.1–13.3	10	Unlikely
O6 V((f))	7.2–10.9	8	Unlikely
Y Cyg:			
O9 V	5.6–11.3	11	Probable
O9.5 V	5.2–11.9	11	Probable
HD 206267:			
O6.5 V((f))	11.3–16.7	>15	Probable
O9.5: V	7.2–12.2	>12	Probable
DH Cep:			
O5.5 III(f)	12.0–16.1	11	No
O6 III(f)	11.0–14.6	10	No
AH Cep:			
B0.2 V	2.9–9.9	7–9	Probable
B2 V	3.3–10.4	7–8	Probable

TABLE 6

Comparison with Models

Star	Orbital Masses ($M_\odot$)	Model Masses ($M_\odot$)	Orbital Mass Ratio	Model Mass Ratio
V453 Cyg:				
B0.7 III	13.0 ± 0.4	11–22	1.23 ± 0.04	0.69–2.22
B1 V	10.6 ± 0.2	9–17		
HD 191201:				
O9.5 V–III......	$>12.9 \pm 2.9$	25–33	1.17 ± 0.28	0.96–1.57
O9.5 V–III......	$>11.0 \pm 0.9$	20–27		
V382 Cyg:				
O6.5 V((f))	29.7 ± 1.1	35–51	1.46 ± 0.09	0.95–1.30
O6 V((f))	20.3 ± 0.9	33–46		
Y Cyg:				
O9 V	16.8 ± 0.5	20–32	0.95 ± 0.04	1.00–1.50
O9.5 V	17.7 ± 0.4	15–28		
HD 206267:				
O6.5 V((f))	$>28.4 \pm 1.5$	38–61	1.64 ± 0.17	1.61–2.95
O9.5: V	$>17.3 \pm 1.5$	17–28		
DH Cep:				
O5.5 III(f)	$34.4^{+2.8}_{-2.5}$	44–62	1.15 ± 0.05	0.84–1.36
O6 III(f)	$29.8^{+2.5}_{-2.4}$	38–54		
AH Cep:				
B0.2 V	$16.2^{+6.0}_{-2.5}$	10–18	1.21 ± 0.05	1.12–1.80
B2 V	$13.3^{+5.5}_{-2.3}$	7–11		

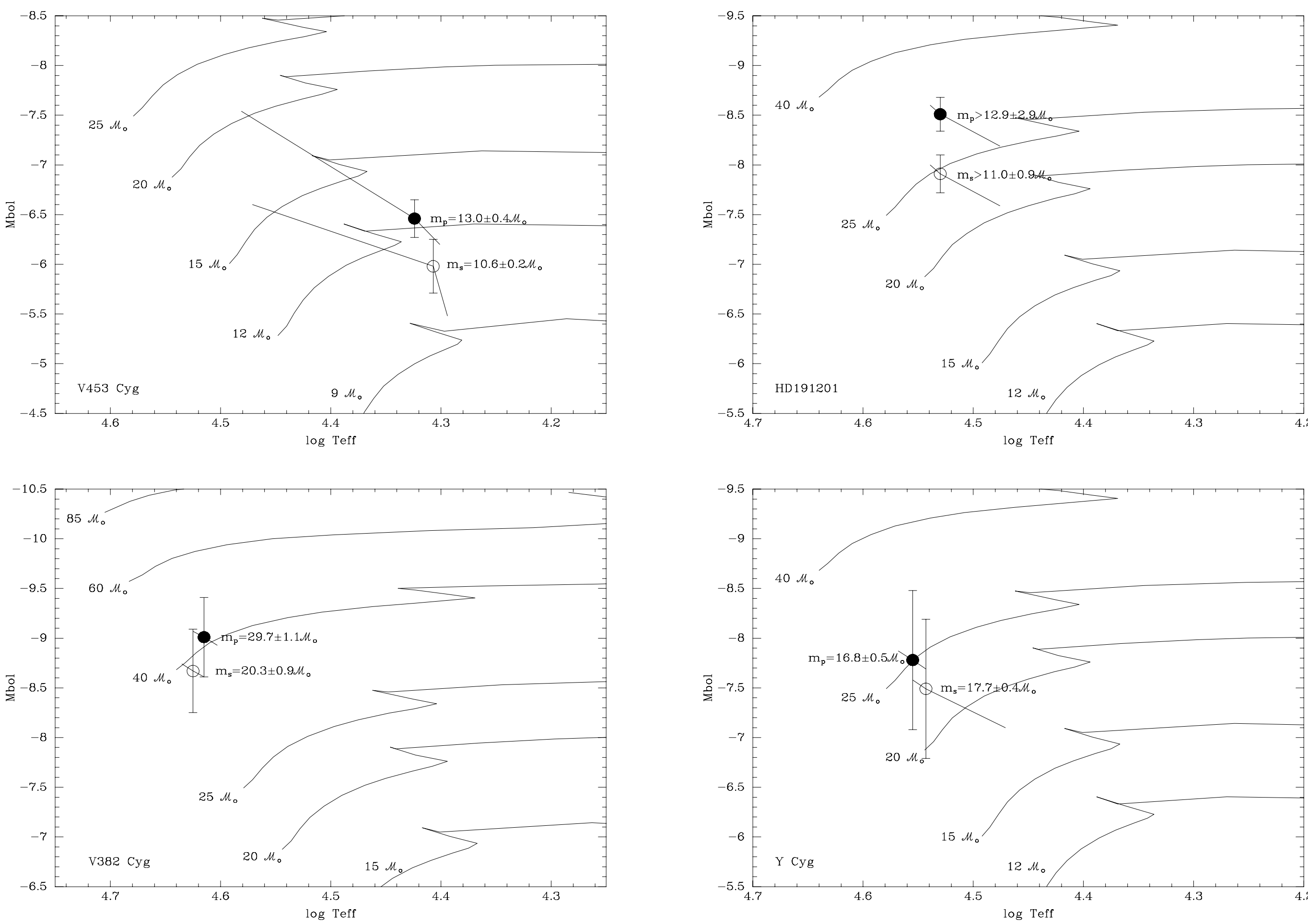

Fig. 2.—Comparison of the orbital masses with stellar evolutionary tracks. The primary is marked with a filled circle; the secondary is marked with an open circle. The horizontal error bar shows the uncertainty in the luminosity, usually dominated by uncertainties in distance. The slanted lines show the errors introduced by an uncertainty of one spectral subtype in classifying the stars; the error bars are diagonal as a change in effective temperature introduces a change in the bolometric correction. The masses marked at the beginning of each track are the initial (zero age) masses, although in most cases the amount of expected mass loss is a single solar mass or less.

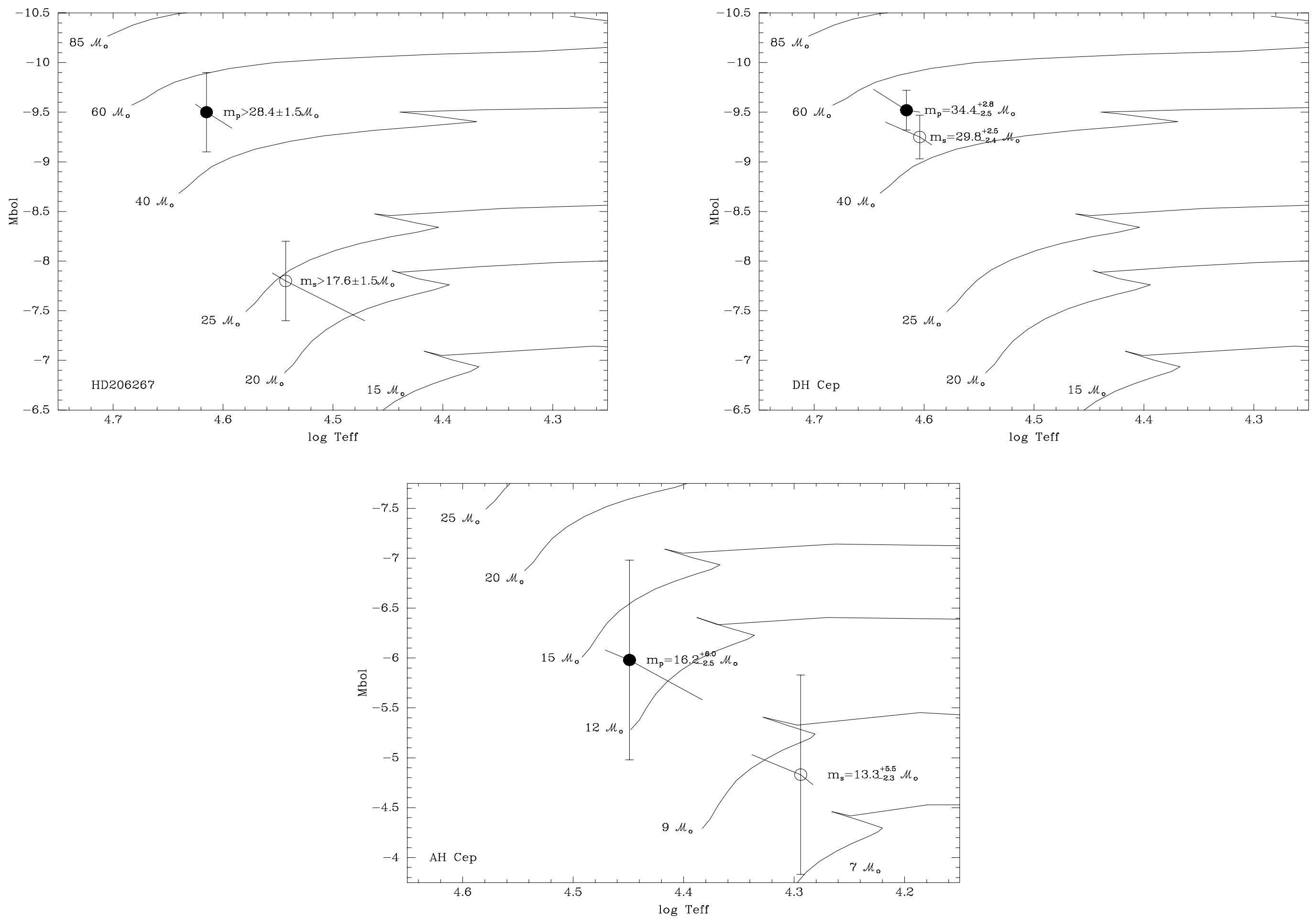

FIG. 2—*Continued*

We find that with two exceptions, there is good agreement between the observed masses and the evolutionary model masses. The two exceptions are DH Cep and V 382 Cyg. In *both* these cases the masses of the stars seem to be considerably less than the masses implied by the models. These are also the only two systems in which the components are overfilling their Roche lobes. It is interesting to note that the masses of *both* components are low; this suggests that in massive binaries with Roche-lobe enhanced mass loss, that much of the mass may be lost to the system rather than transferred. This is consistent with the expected effects of stellar winds on such enhanced mass loss and is accord with Conti's (1996) suggestion that there is no evidence of mass *transfer* in any Wolf-Rayet binaries. Clearly more studies are need to test this.

The errors in the model masses are often dominated by uncertainty in the distances, while the errors in the orbital masses are dominated by uncertainties (or unknown) orbital inclinations. Therefore, we include in Table 6 a comparison of the observed orbital mass ratios with the model mass ratios. (We are grateful to L. Penny for suggesting this test.) The former is independent of the orbital inclination, and the latter is now relatively insensitive to the uncertainty in the distances, as the luminosity (and hence mass) of both components scale together. The uncertainties in the model mass ratios are hence dominated by our assumption of an uncertainty of one spectral subtype for each component. The disadvantage of this test is that it will only be sensitive to problems in systems with unequal components. We do, however, find good agreement between the observations and the models, with the exception of the Roche-filling system V 382 Cyg. We do not see any evidence from these data that there are disagreements between the orbital masses and the evolutionary tracks, although the ranges in allowed mass ratio are large.

Have we, then, resolved the mass discrepancy between the spectroscopic masses and the evolution masses? Herrero et al. (1992) emphasize that the problem is most severe for evolved stars and for the higher masses. Unfortunately, our highest mass, detached system, HD 206267, lacks any measurement an orbital inclination. Nevertheless, even here (in a system with an observed mass ratio far from unity), the observed mass ratio and the mass ratio predicted by the models agree. It would add significantly to resolving this issue if there were a known inclination for HD 191201 and HD 206267.

We *can*, we feel, rule out any discrepancy for stars extending to masses of 15 $M_\odot$ ($M_{\rm bol} = -6$). For instance, there is excellent agreement between the spectroscopic masses and the evolutionary tracks for V453 Cyg (11–13 $M_\odot$) and AH Cep (13–16 $M_\odot$). At 17–18 $M_\odot$, there is reasonable agreement (Y Cyg). The stars of higher mass either are not detached (V382 Cyg and DH Cep) or have only minimum masses (HD 191201 and HD 206267) available.

Let us turn next to the literature to see if we can gain some additional insight for higher masses, even if the orbit solutions are perhaps not as well determined.

4.1. *Other Systems from the Literature*

We have emphasized throughout this paper our concern with the effects of pair blending on orbit determinations of massive stars; given $v \sin i$ values that are typically 100–350 km s^{-1} (Conti & Ebbets 1977), and maximum velocity separations of 300–600 km s^{-1} (Table 3) even for systems that have met our selection criterion (§ 1.1), we approach the issue of adding stars from the literature very cautiously. In particular, we note that even the most modern studies rely on cross-correlation techniques to find radial velocity peaks. However, these methods invariably deal with only a single template at once and, thus, are no better at accounting for pair blending than methods that relied on eyeball estimate of line centers.

Some of the other early-type systems that can be found in Batten et al. (1989)'s *Catalog* and subsequent work were attractive, but we exclude them from the discussion here. For instance, we excluded the system HD 159176 (O7 V + O7 V) with a reasonably well-known inclination and cluster membership (see Conti, Cowley, & Johnson 1975) because both stars appear to be filling their Roche lobes (Thomas 1975), and we want to avoid close systems. We also required systems that were seen near enough to edge-on to either have inclinations known or minimum masses that were sufficiently useful lower limits to help resolve the controversy discussed in the introduction. Thus, even systems like HD 93205, which have very interesting spectral types (O3 V + O8 V), good orbits, and are cluster members (Tr 16), are not included as their inclinations are too low to be useful (Conti & Walborn 1976). Similarly, HD 149404 (Stickland & Koch 1996) and HD 48099 (Stickland 1996) were excluded for the same reasons. Despite the excellent job done by Hill & Fisher (1984) on the B0.5 Ib + B2 V binary HR 7551 in actually detecting the spectrum of the secondary by their cross-correlation technique, we are left unsure of how secure the secondary orbit was given the weakness of the peak. The very high-mass system Sk $-67°$ 105 in the LMC studied by Niemela & Morrell (1986) contains stars of interesting types and luminosities (O4 If + O6 V), but unfortunately the stars appear to be filling their Roche lobes.

There are, however, a few systems of high mass for which the results do shed some light on resolving the mass discrepancy. We had explicitly excluded WR + O systems from our observational program, as there are obvious physical complications: often the various emission lines yield considerably different orbit solutions. (Of course, since the WR component does not have absorption lines, typically, at least we are free of the effects of pair blending!) There are, however, a few WR + O systems with relatively well-determined orbits, cluster membership, measured differences in the light of the two components, and measured inclinations, and long enough periods for the two to be noninteracting. In addition, we briefly consider several other early-type systems, pair blending and all. We describe these systems here.

4.1.1. *HD 186943*

This WN4 + O9.5 V Wolf-Rayet binary was analyzed by Massey (1981). The high minimum masses suggested that the system might be eclipsing, and indeed "nonphotospheric eclipses" were reported by Lamontagne et al. (1996), who find an orbital inclination $i = 55.3° \pm 4.7°$, in good agreement with that derived from polarization measurements. The star is a member of Vul OB2, and Massey (1981) used the measured line strengths of the Balmer lines to derive $\Delta m = 1.3$ mag, with the O star the visually brighter member. The derived estimate of $M_V = -4.3$ is consistent with the spectral type and luminosity class and leads then to a bolometric luminosity $M_{bol} = -7.7$. The stars do not fill their Roche lobes. The minimum mass of the O-type star is 16 ± 2 $M_\odot$ if the N V emission-line semiamplitude is adopted for the WN star (as suggested by Massey), and the implied mass is thus 29 ± 10 $M_\odot$ (where most of the uncertainty comes from the orbital inclination). This may be compared to the nominal mass from the evolutionary tracks of 24 $M_\odot$. For this system at least, there is no indication of any mass discrepancy.

4.1.2. *CV Ser*

This infamous WC8 + O8–9 V Wolf-Rayet binary once showed deep eclipses but at some point "stopped eclipsing"; see Massey & Niemela (1981) and references therein. Nevertheless, small "nonphotospheric eclipses" were measured by Lamontagne et al. (1996), who derive $i = 70.4° \pm 2.3°$, in modest agreement with the polarization value $\sim 80°$. The star is a member of Ser OB2, and Massey & Niemela derive $M_V = -4.5$ for the O-type component, with their measurements suggesting that the two components are equally bright. We would derive a bolometric luminosity of $M_{bol} = -8.1$. The long period and circular orbit suggests that the stars are not filling their Roche lobes. The minimum mass of the O-type star is 19 $M_\odot$, which suggests a mass of 23 ± 1 $M_\odot$. This may be compared with the evolutionary mass of 27 $M_\odot$, again suggesting good agreement between the orbital masses and the theoretical tracks.

4.1.3. *HD 152248*

This O7 Ib double-lined binary was found by Struve (1944), and an improved orbit was given by Hill, Crawford, & Barnes (1974). Very recently, Stickland et al. (1996) used *IUE* data to derive minimum masses of 20.9 ± 0.6 $M_\odot$ and 22.2 ± 0.6 $M_\odot$. A new determination of the orbital inclination is apparently in progress according to the Stickland et al. paper, but a polarization study by Luna (1988) suggests $i = 71°$, with a rather large uncertainty ($i = 60°$ to $i = 76°$). The star is a member of NGC 6231 (distance modulus of 11.6, according to Perry, Hill, & Christodoulou 1991), and if we assume that the two components are equally bright, the system's photometry ($V = 6.15$, $B-V = 0.15$) would suggest each component has $M_V = -6.1$, consistent with the implication that each component is of type O7 Ib (Conti 1988), although Stickland et al. do not explicitly discuss whether there is any difference in the spectral types. We therefore derive $M_{bol} = -9.6$ for the two components. The derived masses are 25^{+7}_{-2} $M_\odot$ for each component. Clearly an improved value for the orbital inclination would help. The nominal evolutionary masses are 47 $M_\odot$, considerably larger than the masses from the spectroscopic orbit. We expect that the radii of these stars to be of order 19 $R_\odot$ each and the Roche radii to be 19 $R_\odot$, so although we again have a system that would appear to be supporting the existence of the "mass discrepancy," we instead find that it is yet another case where stars filling their Roche lobes have masses smaller than single-star evolutionary models would predict.

4.1.4. *HD 166734*

The orbit of this O7 If+O9 I binary was described by Conti et al. (1980). The system has neither a measured inclination nor cluster membership, but the minimum masses of this early-type, luminous system are interestingly high, and its period is long enough that it is unlikely that the stars are filling their Roche lobes. Conti et al. adopt a spectroscopic parallax for the system that would lead to values of the bolometric magnitudes of $M_{\rm bol} = -10.5$ and $M_{\rm bol} = -9.7$. The orbits imply masses of greater than 29 $M_\odot$ and greater than 31 $M_\odot$, while evolutionary tracks would suggest masses of 73 $M_\odot$ and 46 $M_\odot$, respectively. Does this suggest that something is awry for the more luminous star, given that the inclination required for good agreement for the O9 I star would still leave a discrepancy for the more luminous (but slightly less massive) primary?

The answer appears to be "no": if we make the same assumptions that we did in our own analysis, and allow for the possibility of an error of one spectral subtype, and then adopt the Conti (1988) M_V's and the associated errors (as we did in analyzing our own systems), we find that the ranges in evolutionary masses are 33–83 $M_\odot$ for the primary and 33–67 $M_\odot$ for the secondary. Thus, while we cannot use HD 166734 to exclude there being a mass discrepancy at higher masses, neither does it provide any supporting evidence of one.

5. SUMMARY AND CONCLUSIONS

We have obtained new and improved orbits for seven early-type binaries and failed to find improved orbits for an additional five systems. From our new data along with several systems from the literature, we can conclude that there is very good agreement between the evolutionary track masses of Schaller et al. (1992) and the spectroscopic orbit determinations for stars up to 15 $M_\odot$, as demonstrated by V453 Cyg and AH Cep. There is reasonable agreement at 17–18 $M_\odot$ (Y Cyg). Our new spectroscopic orbits will provide additional data for stars of higher masses if orbital inclinations can be determined photometrically for HD 191201 and HD 206267. We note that spectroscopic orbits from the literature confirm good agreement up to a mass of 25 $M_\odot$ (HD 186943 and CV Ser). At higher masses, the scant number of existing spectroscopic orbits either provide neutral results (i.e., HD 166734) due the lack of good distances and/or inclinations, or else the systems are known to fill (or overfill) their Roche lobes and hence have limited applications to the study of single stars. We note that in each of the cases discussed here where the stars are semidetached or in contact, we derived masses for *each* component that are significantly less than that expected from single-star evolutionary models, suggesting that mass lost from each star is generally not accreted onto the companion.

We would like to thank the National Science Foundation for funding the Research Experiences for Undergraduates program at Northern Arizona University. We also thank Kathy DeGioia-Eastwood for providing office space and access to her computer during the summer. We are grateful to the director of NOAO, Sidney C. Wolff, and the Kitt Peak TAC for their support of this project of the project over the many years of observing on the Coude Feed telescope. Graham Hill and Laura Penny both kindly provided copies of their work in advance of publication. We are grateful to Drs. Penny, Artemio Herrero, and especially the referee, Doug Gies, for many thoughtful comments.

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