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SPECTROSCOPIC STUDIES OF O-TYPE BINARIES. IV. HD 165052 AND HD 167771

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ABSTRACT

HD 165052, O6.5 V, and HD 167771, O7.5 III((f)), are double-lined binaries with periods of six and four days, respectively, and velocity semiamplitudes near 100 km s^{-1}. In our spectroscopic orbital analysis, we investigated the effect of correcting the measured radial velocities for pair blending. The derived velocity amplitudes are increased by roughly 7%, and hence the minimum masses increase by 20%–25%. The raw data lead to minimum masses, $m \sin^3 i$, between 2 and 3 $m_\odot$. Since normal O stars are thought to have masses greater than 20 $m_\odot$, the orbits must be highly inclined to the line of sight. From the luminosities and effective temperatures we derived stellar radii. For HD 167771, the requirement that neither component overfill its Roche lobe implies that each has a mass in the neighborhood of 30 $m_\odot$ or larger.

Subject headings: stars: binaries — stars: early-type

I. INTRODUCTION

Because mass loss is important on an evolutionary time scale for O-type stars, the theory of even their early main-sequence evolution presents a special case. Therefore, empirical mass determinations for such stars are especially needed as checks on evolutionary tracks with mass loss, such as those recently computed by de Loore, De Grève, and Lamers (1977) and Chiosi, Nasi, and Sreenivasan (1978). In turn, a thorough understanding of the evolution of massive stars is important for understanding the evolution of X-ray binaries (Cowley 1977), the life cycle of young associations (Mueller and Arnett 1976), and other problems.

This paper presents orbital analyses of two double-lined O-type systems. Conti (1974) first noticed that HD 165052 is double-lined, and Plaskett (1924) discovered double lines in HD 167771 (= HR 6841). To our knowledge, our orbital solution is the first for either star. The composite spectral type of HD 165052 on the system of Conti and Leep (1974) is O6.5 V, and that of HD 167771 is O7.5 III((f)). As the types imply, He II λ4686 is strongly in absorption in both, and HD 167771 shows N III weakly in emission. Both stars show Hα in absorption. Thus both are normal, with no spectroscopically conspicuous mass loss, and are not far from the zero-age main sequence.

Several authors have shown that blending of the two lines in double-lined binaries ("pair blending") decreases the measured velocity separation. Therefore, we derived tentative corrections to the observed velocities, in the expectation that the corrected velocities would at least be closer to the truth than the uncorrected ones. We found that pair blending significantly affects the derived minimum masses. In the following, § II describes the observations, § III the orbital and spectrophotometric analyses, and § IV the results. Section V summarizes our conclusions.

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II. OBSERVATIONS

Table 1 describes the observational material, which consists of high-dispersion spectrograms in the blue on IIa-O emulsion and of four lightly exposed spectrograms in the yellow-red on 098-04 emulsion. The Kitt Peak spectrograms were calibrated spectrophotometrically by means of spot sensitometer plates cut from the same piece of glass as, and developed simultaneously with, the spectrograms. We traced a few of the blue spectrograms with the Boller and Chivens microdensitometer at the High Altitude Observatory, and we measured all the spectrograms for velocity with a Grant oscilloscopic comparator in both forward and reverse directions: the Kitt Peak and Cerro Tololo spectrograms with the machine at the Kitt Peak National Observatory and the David Dunlap spectrograms with the machine at the National Bureau of Standards Boulder Laboratories (Bohannan and Garmany 1978). Table 2 lists the observations.

III. ANALYSIS

a) Orbits

To determine the periods of the two binaries, we used the technique described by Lafler and Kinman (1965). For HD 167771, the period we found is consistent, to within the observational uncertainties, with a much earlier velocity measurement by Buscombe and Kennedy (1965).

The lines we used to determine the velocity are He I λλ3819, 4026, 4471; He II λλ4541, 4686; and Si IV

TABLE 1

OBSERVATIONAL DETAILS

PARAMETER	OBSERVATORY		
	Kitt Peak	Cerro Tololo	David Dunlap
Telescope	90 cm aux. feed	1.5 m	1.9 m
Focus	Coudé	Coudé	Cassegrain
Camera	2	1	G12
Grating order	3 blue, 2 red	2 blue	2 blue
Recip. dispersion (Å mm^{-1})	17 blue, 25 red	19	12
Slit width (arcsec)	3.1	1.4	0.75
Slit width (μm on plate)	25	25	33
Width of spectrum (mm)	0.6 or 0.8	0.6	0.3–0.5
Hypersensitization	Nitrogen baking	Nitrogen baking	Evacuation
Observer	Conti, Morrison	Conti	Bolton
Plate numbers	D-, 4 digits, 1 letter	D-, 3 digits, 1 letter	5 digits

λ4089. All were measurable on nearly all the Kitt Peak and Cerro Tololo plates. With the DDO plates, we used only the He II lines and He I λλ4026, 4471. In HD 165052, we found no systematic difference between He I and He II, and we averaged all the lines together. In HD 167771, there may be a small difference: V(He II) $-$ V(He I) $= 17 \pm 7$ km s^{-1}. Therefore, we present only the elements computed from the average of He I and Si IV. We used the rest wavelengths given by Conti, Leep, and Lorre (1977).

Our least-squares differential-correction routine for computing orbital elements is a version of the program described by Wolfe, Horak, and Storer (1967). Since it analyzes the two velocity curves separately, we give as final values for V_0, e, and ω the average from the two solutions. In both systems, the two individual values of V_0 agree.

b) Light Ratios and Individual Spectral Types

Being unable to find a systematic difference in line depth between the two components of HD 165052, we took the light ratio to be unity and the individual spectral types to be the same as the composite spectral type. For HD 167771, we found the light ratio and the individual types by the method of Petrie (1940) for integrated absorption strength, with the assumption that the two lines are well separated. (At maximum velocity separation, Petrie's validity criterion for this assumption is satisfied.) Since the ratio of the strength of He I λ4471 to that of He II λ4541 determines spectral type on the system of Conti and Alschuler (1971), we applied the method to these lines, and we took the relative behavior of line strength with spectral type from those authors' catalog. We assumed the spectral type of the primary to be O7 III. Although this method is approximate, the quality of the data does not justify any greater sophistication.

c) Pair Blending

Tatum (1968), Batten and Fletcher (1971), Hilditch (1973), and Andersen (1975), among others, have discussed pair blending in double-lined binaries. Since, in our stars, the profiles never reach the level of the continuum between the two lines, we anticipated that pair blending would be important, and we evaluated its effect in He I λ4471. Our approach was to find profiles of single stars that match as well as possible the full width at half-intensity and the depth (corrected for dilution by the other component) of the observed profile of each component. We measured these quantities on four intensity tracings of HD 165052 and two of HD 167771 on which λ4471 is well resolved, and we matched them with the widths and depths read from hand-smoothed profiles from the 7 Å mm^{-1} spectrograms obtained by Morrison (1975*b*). These profiles we shifted with respect to each other, weighted according to the derived light ratio, and added. By judiciously choosing the individual profiles and by adjusting the shift, we ensured that the widths, depths, and separation of the two components in the sum matched those observed. The blending correction for each line is the difference in the position of the center of symmetry of the line between the original profiles and the sum. For smaller separations, such that the components are barely measurable as double on the Grant machine, we used a pair of profiles that matched the well-resolved observed profiles to determine the blending correction in the same way. We fitted a least-squares straight line to the correction as a function of separation. For each component of HD 165052, this line has the equation $\delta V = 11.2 - 0.033\Delta V$ km s^{-1}, where δV is the correction and ΔV is the separation. The corrections for HD 167771 are similar in size, but, because our two tracings gave inconsistent results, we regard these corrections with skepticism.

IV. RESULTS

a) Balmer Velocity Progression

A trend in velocity along the Balmer series, with the stronger lines more negative in velocity, is commonly interpreted (e.g., Bohannan and Garmany 1978) as evidence for an outwardly accelerating atmosphere and, given an adequate theoretical basis, could be used to find a mass-loss rate. We used our single-lined spectrograms to search for this effect, but failed to

TABLE 2

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Plate No.	J.D. ⊙ -2440000	Phase	V_1	V_s	V_2	Plate No.	J.D. ⊙ -2440000	Phase	V_1	V_s	V_2
					HD 165052						
*D-5384a	2560.940	0.342	--	-9	--	D-6325c	2938.861	0.894	--	-1	--
D-5387d	2561.858	0.492	--	+1	--	D-6331c	2939.800	0.047	+101	--	-111
D-5393a	2562.921	0.666	-73	--	+93	D-6339a	2940.918	0.229	+88	--	-81
D-5405c	2565.822	0.138	+95	--	-106	D-6343a	2941.851	0.381	--	+5	--
*D-5409d	2566.850	0.306	--	+1	--	D-6350a	2942.902	0.552	-96	--	+74
D-5624a	2687.587	0.960	--	+12	--	D-6355c	2943.863	0.708	-61	--	+91
D-5629a	2688.588	0.133	+103	--	-121	D-6586a	3089.575	0.440	--	+11	--
D-5636a	2689.591	0.296	+62	--	-91	D-6592a	3090.573	0.602	-105	--	+110
D-5650a	2691.584	0.620	-94	--	+100	D-6598a	3091.579	0.767	-66	--	+101
D-6321a	2937.771	0.716	-63	--	+64	D-6603a	3092.571	0.928	--	+10	--
					HD 167771						
36141	1475.674	0.386	+111	--	*-25	D-5375d	2559.770	0.217	+114	--	-130
36497	1560.559	0.749	-103	--	+148	D-5384b	2560.958	0.516	--	+16	--
36534	1565.551	0.005	--	+9	--	D-5387b	2561.805	0.730	-101	--	+167
36998	1787.817	0.942	--	+1	--	D-5393b	2562.935	0.014	--	+16	--
37057	1822.706	0.723	-110	--	+151	D-5397c	2563.968	0.274	+119	--	-96
D-3847c	1931.670	0.145	+104	--	-103	D-5401c	2564.933	0.517	--	+12	--
D-3850c	1932.660	0.394	+62	--	-81	D-5405d	2565.839	0.745	-88	--	+146
38094	2157.847	0.067	--	+1	--	D-5411a	2566.873	0.005	--	+1	--
38104	2158.816	0.310	+108	--	*-45	D-5414b	2567.773	0.232	+129	--	-83
38117	2162.845	0.324	+105	--	*-73	39639	2629.610	0.794	-71	--	+144
38151	2169.763	0.065	--	+15	--	D-5560b	2668.695	0.630	-77	--	+119
38180	2178.752	0.328	+128	--	*-51	D-5575a	2672.645	0.624	-74	--	+109
38186	2183.726	0.579	-86	--	+43	D-5580a	2673.632	0.873	-94	--	+68
38232	2192.786	0.860	-78	--	+80	D-5624b	2687.607	0.390	+72	--	-82
38264	2201.719	0.108	+77	--	-73	D-5629b	2688.609	0.642	-78	--	+140
38292	2207.717	0.617	-60	--	+99	*D-5636b	2689.622	0.897	--	-4	--
*38310	2220.727	0.891	--	+8	--	D-5650b	2691.597	0.394	+81	--	-68
38329	2225.618	0.122	+54	--	-58	D-5691a	2722.565	0.188	+115	--	-98
†39268	2524.827	0.423	--	+16	--	D-5696a	2723.568	0.440	--	+12	--
D-563d	2528.940	0.458	--	-5	--	D-5748a	2730.565	0.201	+125	--	-101
D-570d	2529.930	0.708	-88	--	+124	†40468	2877.892	0.278	+120	--	-91
D-578b	2530.910	0.954	--	+11	--	†40523	2898.880	0.560	-32	--	+83
D-594c	2533.900	0.707	-95	--	+155	†40539	2908.775	0.051	--	+6	--

*Value omitted from orbital solution.

†Slit width greater than indicated in Table 1.

V_s: velocity measured from single-lined plates; V_1: velocity of star 1; V_2: velocity of star 2. Velocities are in km s^{-1}.

TABLE 3

ORBITAL ELEMENTS

Element*	HD 165052 (all lines)	s.d.	HD 167771 (He I and Si IV)	s.d.
V_0 (km s^{-1})	+3.0	4.6	+9.1	3.6
K_1 (km s^{-1})	91.0	2.8	107.1	4.6
K_2 (km s^{-1})	104.0	8.6	122.9	5.3
e	0.064	0.041	0.000	(assumed)
ω (rad)	5.30	0.97	0.000	(assumed)
T (Julian date)	2442939.5	0.6	2442566.8	0.1
P (days)	6.140	0.002	3.9735	0.0002
$a_1 \sin i$ (10^6 km)	7.7	0.2	5.8	0.3
$a_2 \sin i$ (10^6 km)	8.8	0.5	6.7	0.3
$m_1 \sin^3 i$ (solar masses)	2.5	0.5	2.7	0.3
$m_2 \sin^3 i$ (solar masses)	2.2	0.3	2.3	0.2
m_2/m_1	0.87	0.08	0.87	0.05

* V_0, center-of-mass velocity. K, half-amplitude of velocity variation. e, orbital eccentricity. ω, longitude of periastron, measured from maximum positive radial velocity of star 1. T, time of periastron (HD 165052) or conjunction (HD 167771). a, orbital semimajor axis. P, orbital period. m, stellar mass.

find it in HD 165052. In HD 167771, there appears to be a significant velocity progression, which probably is due to the primary. With respect to the mean velocity of the lines H8–H13, Hγ and Hβ are more negative by 10 ± 4 km s^{-1} and Hα by 37 ± 5 km s^{-1} (internal standard deviations in the mean). Bohannan and Garmany (1978) also find a Balmer progression in at least one O((f)) star of luminosity class III.

b) *Orbits*

Table 3 presents the derived orbital elements for the two stars, with internal standard deviations calculated by the orbital analysis program, and Figures 1 and 2 present the observed and calculated radial velocities. None of this material contains the correction for pair blending. For HD 165052 the computed velocity curves fit the data reasonably well, but for HD 167771 the fit is poor for the secondary and marginal for the primary. In both components of HD 167771, the velocities attain larger positive values than negative ones; therefore, the individual orbital solutions both yield eccentricities near 0.1, with periastron at maximum positive velocity. This situation is physically impossible, and the derived eccentricities must be spurious. Since the velocity curves are based almost entirely on three He I triplet lines, which have extended blue wings due to the presence of a forbidden component, pair blending would affect negative velocities more than positive velocities, especially for the secondary. Thus the observed effect is in the right sense to be due to pair blending. If it is, however, then we undercorrected for blending, since our correction did not remove the asymmetry in the velocity curves. We can offer no convincing explanation for the asymmetry, and we set the eccentricities to zero in order to derive the orbital elements in Table 3.

The effect of the blending correction on the derived orbital elements is as follows: The eccentricity is reduced by 0.02 in HD 165052 but not at all in HD

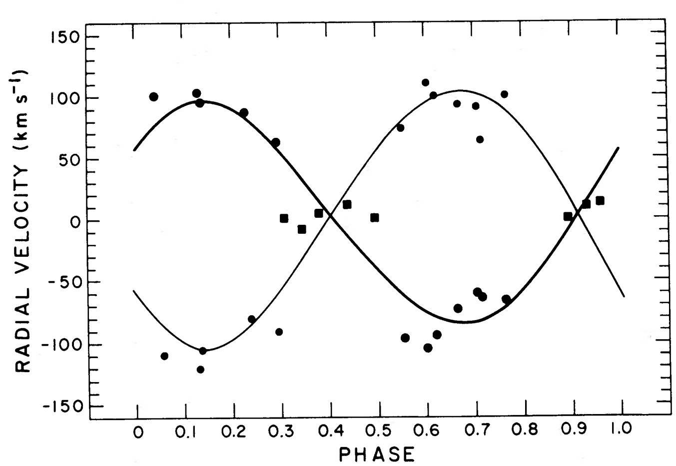

FIG. 1.—Observed radial velocity as a function of orbital phase (calculated according to the elements in Table 3) and the corresponding theoretical curves for HD 165052. The larger symbols and heavier curve refer to the more massive star. Squares denote single-lined spectrograms.

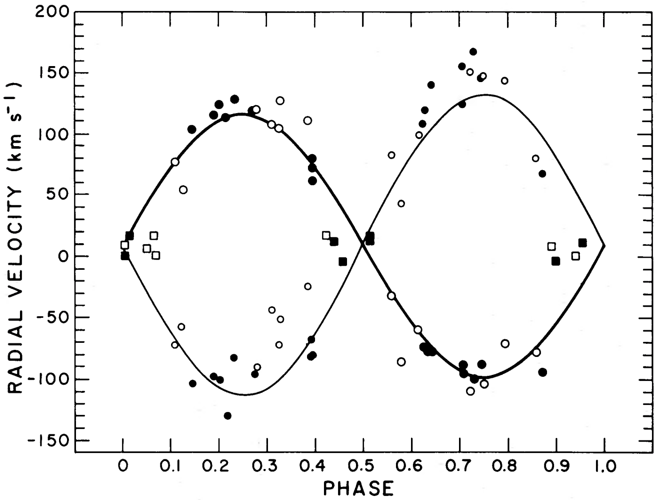

FIG. 2.—Observed radial velocity as a function of orbital phase (calculated according to the elements in Table 3) and the corresponding theoretical curves for HD 167771. The larger symbols and heavier curve refer to the more massive star. Open symbols denote spectrograms from the David Dunlap Observatory; filled symbols denote spectrograms from Kitt Peak and Cerro Tololo; and squares denote single-lined spectrograms.

167771. For both systems, the velocity semiamplitudes increase by about 7%. Since the minimum mass is proportional to the cube of the semiamplitude, the effect on the masses is substantial, roughly 20%–25%.

c) *Systemic and Interstellar Velocities*

The center-of-mass radial velocities to be expected from circular galactic rotation (Cruz-González *et al.* 1974) are $+5$ km s^{-1} for HD 165052 and $+15$ km s^{-1} for HD 167771. These values agree with the derived values of V_0 and show that neither star is a runaway. In HD 165052 and HD 167771, the velocity of the interstellar Ca II K line is -15 ± 1 km s^{-1} and -11 ± 1 km s^{-1}, respectively.

d) *Stellar Properties*

Table 4 summarizes the nondynamical properties of the individual stars in the two binary systems. We derived the absolute visual magnitudes from distance moduli given by Conti and Alschuler (1971) and from V magnitudes determined by Morrison (1975*a*). The spectral types are on the classification system of Conti and Leep (1974); see § III*b*. We obtained projected rotational velocities, $V \sin i$, from the full width at half-intensity of the individual profiles of He I λ4471 by the method of Conti and Ebbets (1977). Effective temperatures are on the scale of Conti (1973), bolometric corrections are from Morton (1969), and the radii R follow from the definition of effective temperature. The given uncertainties in the radii are derived from the uncertainties in absolute bolometric magnitude $M_{\rm bol}$ and in $T_{\rm eff}$. From the luminosities and temperatures, it is clear that all four stars lie above the zero-age main sequence in the theoretical H-R diagram.

For the mass ratios in Table 3, we investigated whether the luminosities in Table 4 are consistent with the mass-luminosity relation for the main sequence. For the zero-age models by Chiosi *et al.*,

TABLE 4
STELLAR PROPERTIES

	HD 165052				HD 167771			
PROPERTY	Star 1	s.d.	Star 2	s.d.	Star 1	s.d.	Star 2	s.d.
Observational:								
M_V	-4.9	0.2	-4.9	0.2	-5.8	0.2	-5.2	0.2
Spectral type	O6.5 V	...	O6.5 V	...	O7 III((f))	...	O9 III	...
$V \sin i$ (km s^{-1})	65	9	69	4	92	15	62	15
Derived:								
$T_{\rm eff}$ (10^3 K)	40.0	0.8	40.0	0.8	38.5	0.8	34.5	0.8
$M_{\rm bol}$	-8.6	0.2	-8.6	0.2	-9.4	0.2	-8.4	0.2
R (10^6 km)	6.8	0.7	6.8	0.7	10.5	1.1	8.3	0.9
$V_{\rm syn}$ (km s^{-1})	80	8	80	8	193	20	152	16

$L \propto m^{2.3}$, independent of the effects of mass loss. We used our derived mass ratios with this relation to predict luminosity ratios. In HD 165052, the luminosity of the secondary is predicted to be 0.73 ± 0.16 that of the primary. Since this difference might have gone undetected in our spectrograms, the mass-luminosity relation may be consistent with the observations. In HD 167771, the primary is observed to be slightly overluminous with respect to the secondary and superluminous with respect to the zero-age mass-luminosity relation. This discrepancy is consistent with the primary being more evolved than the secondary, since the stars brighten as they first leave the zero-age main sequence. The uncertainties in our mass and luminosity ratios are such that, with the masses themselves undetermined, we cannot distinguish between evolutionary tracks with and without mass loss.

Table 4 also gives the rotational velocity that would correspond to synchronism with the orbital motion: $V_{\text{syn}} = 2\pi R/P_{\text{orb}}$. The assumption of synchronism yields an estimate for the orbital inclination i: $(\sin i)_S = V \sin i/V_{\text{syn}}$. For HD 165052, this relation would imply $(\sin i)_S \approx 1$ and in turn would require an implausibly small mass. Therefore, either the rotation is faster than synchronous ($V > V_{\text{syn}}$) or a substantial fraction of the observed line width is due to macroturbulence (Ebbets 1977). In the latter case, synchronism is possible. For HD 167771, $(\sin i)_S = 0.45 \pm 0.10$, and synchronism is a possibility.

Since both systems may be synchronous, we calculated the radius of the Roche lobe for all four cases, using the approximate formula of Plavec (1968). All we know from observation is $a \sin i$, and we multiplied each side of his equation by $\sin i$:

$$R_1{}^L \sin i = (a_1 + a_2) \sin i \left(0.38 + 0.2 \log \frac{m_1}{m_2}\right),$$

$$R_2{}^L \sin i = (a_1 + a_2) \sin i \left(0.38 + 0.2 \log \frac{m_2}{m_1}\right). \quad (1)$$

For both components of HD 165052, $R^L \sin i = 6 \times 10^6$ km, similar to the radii in Table 4. Since $\sin i$ is probably less than 1, the stars do not fill their Roche lobes, and we conclude that ellipsoidal light variations are unlikely. For HD 167771, $R_1{}^L \sin i = (4.8 \pm 0.2) \times 10^6$ km and $R_2{}^L \sin i = (4.6 \pm 0.2) \times 10^6$ km; both are smaller than the stellar radii in Table 4. We may obtain a limit on $\sin i$ from the fact that the stars may not greatly overfill their critical surfaces: $(\sin i)_R \leq R^L \sin i/R$. If the equality sign holds, the stars exactly fill their Roche lobes. Applying this relation to the stars separately, we obtain nearly equal values whose mean is $(\sin i)_R \leq 0.50 \pm 0.05$. Above, we independently obtained $(\sin i)_S = 0.45$, which is near the lower limit on $(\sin i)_R$. This rough equality implies that, if rotation and revolution are synchronous, then the components fill their Roche lobes. Furthermore, unless macroturbulence is important, the rotation may be faster than synchronous rotation but may not be slower.

When the minimum masses are increased to compensate for pair blending, our limit on $\sin i$ implies that the masses of the primary and secondary are at least 29 ± 10 and $26 \pm 10\, m_\odot$, respectively. The uncertainty is large because $\sin i$ enters as the cube; it, in turn, is uncertain primarily because of the uncertainty in the photometric and spectroscopic determination of the stellar radii.

To estimate values (not lower limits) for the masses of the components of HD 167771, we would need an independent estimate of i from a light curve. Since these stars may fill their Roche lobes, ellipsoidal variations are a strong possibility. It may be possible to solve for i by the technique of light-curve synthesis (Hill and Hutchings 1973; Wilson and Devinney 1971), but the fact that i is of order 30° or smaller means that the amplitude of the light curve will be small and the solution poorly determined (Wilson 1977). Morrison's (1974*a*, Table 2) photometry did not show variability in either HD 165052 or HD 167771, but that study was not designed to detect small-amplitude variability. Amplitudes less than or equal to about 0.03 mag could have gone undetected.

V. CONCLUSIONS

By correcting the radial velocities for pair blending, we have shown that it affects the determination of the orbital eccentricity and the velocity semi-amplitude. Although our corrections are not ideal, they yield semiamplitudes that are closer to the truth than the raw ones. The effect on the derived minimum mass is substantial, and pair blending should be explicitly accounted for whenever the separation of the two lines is less than about 4 times the line width.

Both HD 165052 and HD 167771 are normal, slightly evolved O-type systems. In the primary component of the latter system, Hα is significantly blue-shifted relative to the higher Balmer lines, and we infer substantial though not dramatic mass loss. Both orbital solutions yield minimum masses in the range 2–3 $m_\odot$. For HD 167771, the fact that neither star may overfill its Roche lobe sets a limit on the inclination and hence requires the masses to be at least 30 $m_\odot$. This star may turn out to show ellipsoidal variability, but neither binary is likely ever to provide a reliable mass determination, since both orbital planes have a large inclination to the line of sight.

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