ORBITS OF FOUR VERY MASSIVE BINARIES IN THE R136 CLUSTER

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ABSTRACT

We present radial velocity and photometry for four early-type, massive, double-lined spectroscopic binaries in the R136 cluster. Three of these systems are eclipsing, allowing orbital inclinations to be determined. One of these systems, R136-38 (O3 V + O6 V), has one of the highest masses ever measured for the primary, 57 $M_\odot$. Comparison of our masses with those derived from standard evolutionary tracks shows excellent agreement. We also identify five other light variables in the R136 cluster that are worthy of follow-up study.

Subject headings: binaries: eclipsing — binaries: spectroscopic — Magellanic Clouds — stars: early-type — stars: evolution

1. INTRODUCTION

Empirical checks on the mass-luminosity relation and on how well the evolutionary models match reality are sorely lacking for high-mass (>20 $M_\odot$) stars, even near the zero-age main sequence (ZAMS). It has long been recognized that evolutionary tracks (past the ZAMS) are affected by mass loss (see, e.g., Brunish & Truran 1982), and it is now well recognized that in particular the models are highly sensitive to how mixing of material to and from the core is treated (Maeder & Conti 1994), with the most recent work emphasizing the importance of rotation in this regard (Meynet & Maeder 2000; Maeder & Meynet 2000; Heger & Langer 2000; Heger, Langer, & Woosley 2000). Yet these models, untested as they may be, provide the only means for linking a variety of observational studies to astrophysical interpretation, such as the determination of the initial mass function (Massey 1998) and the determination of turnaround masses in clusters containing massive stars (Massey, Waterhouse, & DeGioia-Eastwood 2000; Massey, DeGioia-Eastwood, & Waterhouse 2001).

Herrero et al. (1992) first called attention to a significant mass discrepancy between the masses derived from modern stellar atmosphere models that inferred from stellar evolution codes for the highest mass stars, in the sense that the evolutionary tracks predict a mass as much as 2 times larger. (See also Herrero, Puls, & Villamariz 2000.) Burkholder, Massey, & Morrell (1997) recently tried to resolve this mass discrepancy by using data on massive spectroscopic binaries. They found good agreement between the binary masses and the evolutionary tracks up to 25 $M_\odot$. Some higher mass systems did show significant lower masses than the evolutionary tracks would suggest, but these systems were either at or near their Roche lobes, suggesting that significant mass might have been lost from the system. (See also Penny, Gies, & Bagnulo 1999.)

Massey & Hunter (1998) recently obtained spectra of 65 of the bluest, most luminous stars in the R136 cluster located at the heart of the 30 Doradus nebula in the Large Magellanic Cloud (LMC). The majority of these stars proved to be of spectral type O3, the hottest, most luminous, and most massive stars known. Four of the stars showed widely spaced double absorption lines, indicative of spectroscopic binaries caught at favorable phases. Since the evolutionary masses of these stars were very high, it was thought that these would be excellent candidates for additional study, in hopes that orbit solutions would resolve the mass discrepancy once and for all.

2. OBSERVATIONS AND REDUCTIONS

2.1. The Data

The data were all obtained as part of a Cycle 8 Hubble Space Telescope (HST) program, GO-8217. We utilized 30 orbits, organized into 15 “visits” of two consecutive orbits, with each visit separated by carefully planned intervals. We used the Space Telescope Imaging Spectrograph (STIS) in imaging mode for photometry of our binaries and with a medium-dispersion grating for spectroscopy of each binary.

Each visit began with a pair of short images (total integration time of 2.2 s) obtained with the “long-pass” filter (which cuts off all light <5500 Å) and centered on the middle of the cluster. The 28” × 51” field of view always contained our four binaries, but changes in the spacecraft roll angle resulted in some of the outlying R136 stars being occasionally excluded. The spatial scale was 0.05 pixel⁻¹.

After centering upon a fairly isolated offset star (Melnick 34, or R136-8; see Fig. 1 of Massey & Hunter 1998), the
telecope was precisely offset to each of the four binaries in turn in order to obtain spectra with the G430M grating centered at 4451 Å. These exposures covered the wavelength range of 4310–4590 Å at a dispersion of 0.28 Å pixel$^{-1}$, with a nominal 1.5 pixel resolution of 0.42 Å (28 km s$^{-1}$). This wavelength region was selected to include as many spectral lines as possible in a single wavelength setting, i.e., H$_2$, He i λ4471, and He ii λ4542. We used the 0.2 × 5/2 slit. Wavelength calibration was obtained for each exposure using the default HST/STIS scheme, resulting in a new calibration exposure prior to the first spectroscopic exposure for each orbit.

Near the end of each visit, another pair of short-exposure images (total integration time of 2.6 s) were obtained to continue the photometric monitoring. The total elapsed time for each visit was 3.2 hr.

In order to maximize our phase coverage for all periods of interest, we adopted a clever scheme developed by A. Saha for observing Cepheids as part of the distance scale key project: we designed our program so that each visit was separated in time according to a geometrical progression, corresponding to $\text{gap}(n) / \text{(days)} = 0.5 \times 1.175^n$, $n = 1, 1.4$. The multiplicative and geometrical factors are chosen to assure good phase coverage for the shortest and longest periods of interest, given a predetermined number of observations. Simulations showed that this would provide uniformly good phase coverage for periods from less than 1 day through 30 days. The longest interval between successive visits was 3.7 days, and the shortest interval was 0.5 days.

The observations spanned an observing “season” of 24.4 days. In arranging the order of our visits, we put all the shorter intervals near the middle of the 24 day sequence, with progressively longer intervals toward either end. The intended result of this was that any eclipses would tend to be found in the middle of the sequence, as we find in § 3.6 is indeed the case.

### 2.2. Photometry

For the STIS images, we used the “standard pipeline” flat-fielded images prior to cosmic-ray (CR) rejection. They had been observed in “CR split” mode, resulting in a pair of images, each of 1.1–1.3 s duration. We chose to perform photometry of all 60 images and rejected CR events by comparing the photometry from each of the CR split images. If the photometry agreed to within the photometric errors (3 $\sigma$), we averaged the results; if not, we assumed that the smaller magnitude was spurious owing to a CR event. The photometry was measured using aperture photometry routine of IRAF, with a radius of 2 pixels and with sky determined from the modal value within an annulus lying 5–10 pixels from the center of the star. The point-spread function has a full width at half-radius of 1.7 pixels, and we found that the centers were well determined by a Gaussian fit to the radial profile.

In order to provide more accurate differential photometry for our binaries and to search for other light variables, we performed photometry of 59 of the brightest, most isolated stars in the cluster, including our four binaries. Of the 59 stars, one happened to lie outside the field of view for two of the visits owing to the slightly changing roll angle of the spacecraft over the course of the observations. After eliminating possible variables (based upon whether frame-to-frame agreement was within the photometric errors), we found that there were indeed photometric zero-point changes of ~0.04 mag from frame to frame, with the drifts being secular rather than random in time; i.e., over the course of several days the zero point would drift upward and then downward again. This is consistent with the claim that “instrumental [in]stability” limits absolute photometry with STIS to 5% (Table 16.3 in Leitherer et al. 2001).

In any event, our use of STIS as an N-star photometer (with $N \sim 58–59$) resulted in photometry with high precision for temporal changes.

We have applied a single adjustment to the photometric zero point to have the photometry roughly match $V$; a single value worked well, as the colors of these stars are all very similar (Hunter et al. 1997).

### 2.3. Spectroscopy

Owing to the extreme crowding in the R136 cluster, the spectra for each of the four binaries had to be reextracted with a small aperture centered on each target, with care being taken to select “clean” sky on either side of the slit. We actually reduced our spectra in two ways. For one version, we began with the pipeline final two-dimensional spectrum (flat-fielded, CR removed, geometrically corrected, and wavelength calibrated) and simply reextracted the spectra of our binaries. For the other, we began with the flat-fielded version and extracted our spectra using the usual IRAF routines; for these we also applied our own dispersion solution determined from the wavelength calibration frames. We found in practice that our own reductions provided better signal-to-noise ratio.

In measuring the spectra, we fit double lines using two Vogt functions; this provides excellent fits to even blended double lines and avoids issues with pair blendings, always a concern with orbit solutions of broad-lined stars (see discussion in Burkholder et al. 1997). The single-lined phases were measured with a single Vogt function for consistency. Both versions of the spectra were measured independently, and the results were compared; no systematic differences were found, and the comparison proved useful mainly for eliminating any spurious measurements due to noise spikes. Our measuring error was 5–10 km s$^{-1}$.

### 3. RESULTS

We provide the photometric data and radial velocity data in Tables 1 and 2. In this section we describe what we learned from the spectra of each binary and provide details of the orbit solutions and analysis of the light-curve information. We also report the discovery of five more light variables in the R136 cluster. We begin by explaining our methods.

#### 3.1. Methodology

For the period searches, we used a version of the Lafler & Kinman (1965) routine that relies on point-to-point smoothness after the data (either photometric or radial velocity) are sorted in phase according to a trial period. For the orbit solutions, we initially solved for each component independently using a modified version of the differential corrections program of Wolfe, Horak, & Storer (1967), fixing only the period. In all cases we found solutions consistent with circular orbits, which we expect given the short periods and high masses (see § 4). We then determined the best values of the orbital semiamplitudes $K$ “center-of-
| Image Name | Modified Julian Date | Orbital Phase | Primary | Secondary | Single |
|------------|----------------------|---------------|---------|-----------|--------|
| R136-38    |                      |               |         |           |        |
| o59001020  | 51,622.80            | 0.41          | ...     | 548       | 202    |
| o59002020  | 51,626.29            | 0.44          | ...     | 473       | 219    |
| o59003020  | 51,629.63            | 0.43          | ...     | 486       | 219    |
| o59004020  | 51,632.17            | 0.18          | 118     | 626       | ...    |
| o59005020  | 51,633.40            | 0.54          |         |           | ...    |
| o59006020  | 51,634.03            | 0.73          | 450     | −118*     | ...    |
| o59007020  | 51,634.55            | 0.88          | ...     | −32       | 403    |
| o59008020  | 51,635.39            | 0.13          | 145     | 581       | ...    |
| o59009020  | 51,635.97            | 0.30          | 112     | 650       | ...    |
| o59010020  | 51,636.91            | 0.58          | ...     |           | ...    |
| o59011020  | 51,638.31            | 0.99          | ...     | 242       | 279    |
| o59012020  | 51,639.32            | 0.29          | 117     | 647       | ...    |
| o59013020  | 51,640.25            | 0.86          | 418     | −96       | ...    |
| o59014020  | 51,643.45            | 0.51          | ...     |           | 265    |
| o59015020  | 51,647.15            | 0.60          | ...     | 19        | 332    |
| R136-39    |                      |               |         |           |        |
| o59001030  | 51,622.84            | 0.56          | ...     | 190       | 262    |
| o59002030  | 51,626.34            | 0.42          | 141*    | 412       | ...    |
| o59003030  | 51,629.67            | 0.24          | 80      | 514       | ...    |
| o59004030  | 51,632.20            | 0.86          | 429     | 53        | ...    |
| o59005030  | 51,633.42            | 0.16          | 102     | 481       | ...    |
| o59006030  | 51,634.04            | 0.31          | 97      | 509       | ...    |
| o59007030  | 51,634.56            | 0.44          | ...     | 343       | 218    |
| o59008030  | 51,635.42            | 0.65          | 429     | 57        | ...    |
| o59009030  | 51,635.98            | 0.79          | 454     | 9         | ...    |
| o59010030  | 51,636.92            | 0.02          | ...     | 288*      | 251    |
| o59011030  | 51,638.36            | 0.38          | 120     | 446       | ...    |
| o59012030  | 51,639.36            | 0.62          | 431     | 69        | ...    |
| o59013030  | 51,641.31            | 0.10          | 148     | 448       | ...    |
| o59014030  | 51,643.46            | 0.63          | 425     | 45        | ...    |
| o59015030  | 51,647.21            | 0.56          | 355*    | 148*      | ...    |
| R136-42    |                      |               |         |           |        |
| o59001040  | 51,622.86            | 0.27          | 2       | 578       | ...    |
| o59002040  | 51,626.34            | 0.48          |         | ...       | 250    |
| o59003040  | 51,629.69            | 0.64          | 468     | 15        | ...    |
| o59004040  | 51,632.20            | 0.51          | ...     | ...       | 279    |
| o59005040  | 51,633.45            | 0.94          | ...     | ...       | 290    |
| o59006040  | 51,634.05            | 0.15          | 57      | 548       | ...    |
| o59007040  | 51,634.53            | 0.31          | 18      | 586       | ...    |
| o59008040  | 51,635.43            | 0.62          | 470     | −7        | ...    |
| o59009040  | 51,635.99            | 0.82          | 529     | −29       | ...    |
| o59010040  | 51,636.93            | 0.14          | 56      | 535       | ...    |
| o59011040  | 51,638.38            | 0.64          | 505     | −2        | ...    |
| o59012040  | 51,639.38            | 0.99          | ...     | ...       | 274    |
| o59013040  | 51,641.39            | 0.69          | 530     | −32       | ...    |
| o59014040  | 51,643.48            | 0.41          | 128     | 496       | ...    |
| o59015040  | 51,647.22            | 0.70          | 552     | −73       | ...    |
| R136-77    |                      |               |         |           |        |
| o59001050  | 51,622.92            | 0.29          | −33     | 615       | ...    |
| o59002050  | 51,626.41            | 0.15          | 87      | 561       | ...    |
| o59003050  | 51,629.74            | 0.92          | 454     | 77        | ...    |
| o59004050  | 51,632.23            | 0.25          | −30     | 602       | ...    |
| o59005050  | 51,633.47            | 0.90          | 458     | 116       | ...    |
| o59006050  | 51,634.07            | 0.22          | −11     | 600       | ...    |
components of a massive binary will differ owing to the photometric error for R366-38 is \( \pm 0.010 \) mag. Based on the orbital parameters given subsequently.

mass \( \gamma \) velocities by running a nonlinear least-squares routine based on the grid search program of Bevington (1969), with the eccentricity, time of conjunction, and periods fixed for the two components. This then maximizes the precision of our determination of \( \gamma \) and \( K \). As a reminder, we expect that the \( \gamma \) velocities of the two components of a massive binary will differ owing to the photo-

TABLE 2

| Image Name | Modified Julian Date | Orbital Phase | Primary | Secondary | Single |
|------------|----------------------|---------------|---------|-----------|--------|
| o59001010... 51,622.78 | 0.39 | 14.61 | 14.61 | 15.27 |
| o59001060... 51,622.93 | 14.36 | 14.60 | 15.30 |
| o59002010... 51,626.28 | 14.35 | 14.62 | 15.40 |
| o59002060... 51,626.47 | 14.51 | 14.60 | 15.49 |
| o59003010... 51,629.61 | 14.34 | 14.60 | 15.29 |
| o59003060... 51,629.76 | 14.39 | 14.59 | 15.28 |
| o59004010... 51,636.89 | 14.38 | 14.63 | 15.24 |
| o59004060... 51,636.98 | 14.34 | 14.65 | 15.22 |
| o59005010... 51,638.30 | 14.54 | 14.61 | 15.60 |
| o59005060... 51,638.45 | 14.47 | 14.60 | 15.42 |
| o59006010... 51,639.30 | 14.32 | 14.59 | 15.70 |
| o59006060... 51,639.46 | 14.32 | 14.60 | 15.60 |
| o59007010... 51,641.24 | 14.35 | 14.59 | 15.47 |
| o59007060... 51,641.40 | 14.34 | 14.62 | 15.27 |
| o59008010... 51,643.41 | 14.47 | 14.61 | 15.24 |
| o59008060... 51,643.55 | 14.49 | 14.60 | 15.26 |
| o59009010... 51,647.14 | 14.36 | 14.60 | 15.22 |
| o59009060... 51,647.30 | 14.32 | 14.61 | 15.26 |
| o59010010... 51,652.16 | 14.35 | 14.61 | 15.29 |
| o59010060... 51,652.26 | 14.33 | 14.60 | 15.26 |
| o59011010... 51,653.39 | 14.59 | 14.61 | 15.37 |
| o59011060... 51,653.51 | 14.36 | 14.60 | 15.33 |
| o59012010... 51,654.02 | 14.34 | 14.60 | 15.24 |
| o59012060... 51,654.10 | 14.32 | 14.62 | 15.24 |
| o59013010... 51,654.52 | 14.33 | 14.60 | 15.49 |
| o59013060... 51,654.64 | 14.34 | 14.61 | 15.60 |
| o59014010... 51,655.36 | 14.34 | 14.61 | 15.28 |
| o59014060... 51,655.51 | 14.33 | 14.61 | 15.68 |
| o59015010... 51,656.96 | 14.35 | 14.59 | 15.25 |
| o59015060... 51,656.04 | 14.33 | 14.61 | 15.23 |

a The photometric error for R366-38 is \( \pm 0.007 \) mag.

b The photometric error for R366-39 is \( \pm 0.009 \) mag.

c The photometric error for R366-42 is \( \pm 0.010 \) mag.

d The photometric error for R366-77 is \( \pm 0.027 \) mag.

spheric outflow velocities of the stellar winds (Massey & Conti 1977). We characterize the agreement between the orbit and velocity data by R1, computed from the goodness of fit \( \chi \).

The spectral types and magnitude difference between the components can be determined from the best double-lined phases. Our spectral types differ slightly from those of Massey & Hunter (1998), as these STIS spectra have considerably higher resolution and better signal-to-noise ratio. The relative strengths of He \( \alpha \) \( 4542 \) and He \( \beta \) \( 4471 \) helped establish the spectral class; the absolute visual magnitudes were consistent with all of these stars being dwarfs. The magnitude difference could be measured from the relative fluxes of the \( H_{\alpha} \) lines at double-lined phases, as the equivalent width of \( H_{\alpha} \) is fairly insensitive to \( T_{\text{eff}} \) for dwarfs this hot.

We measured the projected rotation velocity \( v \sin i \) for each component by using the appropriate model atmosphere lines and convolving these with rotational velocities until we obtained the best fit to a line. The model atmosphere code is that described by Kudritzki & Puls (2000), and we used models computed by P. Massey for stars of similar spectral types in the LMC. Given the intrinsic line widths, we found we could not measure rotational velocities smaller than 90–100 km s\(^{-1}\). In the following, we compare the rotational velocities to that expected on the basis of synchronous rotation, computed using the stellar radii and orbital period.

We thus know a great deal about the physical parameters of these stars, which is helpful in reducing the number of free parameters in interpreting the light curves. We adopt a distance modulus \((m - M)_0 = 18.5\), in accord with Westerlund (1977) and van den Bergh (2000). Accurate values of the reddening were determined by Massey & Hunter (1998) based upon the multiband HST photometry of Hunter et al. (1997). Thus, the absolute visual magnitudes are known (Table 1 of Massey & Hunter 1998) for the combined systems, and combined with the magnitude differences measured from the spectra, they tell us \( M_V \) for each component in the binary. The spectral type allows us to assign effective temperatures; we adopt the scale of Chlebowski & Garmany (1991). (We discuss this in more detail in § 4.) The effective temperature then determines the bolometric correction (Vacca, Garmany, & Shull 1996), and hence we know the bolometric luminosity of each star.
We used the light-curve synthesis code GENSYN (Mochnacki & Doughty 1972) to produce model light curves. Our approach was to make a constrained fit using as much data as possible from the spectroscopic results, as described above. The orbital parameters were taken from the spectroscopic solution, and the physical parameters were estimated from the spectral classifications of the stars. We set the stellar temperatures according to the spectral classification. We then estimated the physical fluxes and limb-darkening coefficients from tables in Kurucz (1979) flux models and from Claret (2000), respectively. The observed flux ratios together with the adopted effective temperatures yield estimates of the ratio of stellar radii. Then, for a given input value of the polar radius of the primary $R_p$, we calculated the secondary radius. Each trial run of GENSYN was set by two independent parameters, the system inclination $i$ and the primary polar radius $R_p$. For each run, we attempt to match two observables: the absolute visual magnitude of the system and the eclipse depths and widths. The best-fit solutions are those with the calculated $M_V$ of the system that also matched the eclipse depths. Models that fit the eclipse depths could be made for a range of inclinations; however, the $M_V$ for such models would greatly diverge from that calculated using the well-known distance and reddening to the LMC. The quoted errors in inclination derive from an estimated error of $\pm 0.15$ mag on our $M_V$ values, which is based upon the uncertainty in the LMC distance modulus (van den Bergh 2000) and a modest error in the photometry and reddening (Massey & Hunter 1998).

For all four systems, the stars are well contained within their Roche surfaces. In the case of R136-39, no eclipses are seen. However, the crucial phases where we might expect eclipses lack observations. Therefore, we quote only an upper limit on the inclination. Any inclination above this value would result in eclipses that would be both too deep and too wide to agree with the current observations.

As a further check on the models, we independently estimated the orbital inclination simply from geometry after measuring the eclipse depths. For this we adopt a modest correction for limb darkening using a linear coefficient (Al-Naimiy 1978; van Hamme 1993) but ignore reflection and other second-order effects. Given the poor sampling in phase space, we expected only modest agreement with the models, but in fact the agreement was excellent, giving us high confidence that the orbital inclinations are well determined.

We estimate the errors on the physical parameters, including a 10% uncertainty in the effective temperature scale for O-type stars (Conti 1988). Nevertheless, our parameters are well determined, in large part because the inverse dependence of the stellar radii on effective temperature is partially canceled by the dependence of the bolometric correction on effective temperature, and in fact the uncertainties in $\Delta m$ dominate the errors on the stellar radii:

$$\frac{L}{L_\odot} = \left(\frac{R}{R_\odot}\right)^2 \frac{T_{\text{eff}}}{T_{\text{eff,0}}}^4,$$

$$\frac{R}{R_\odot} = \left(\frac{L}{L_\odot}\right)^{0.5} \frac{T_{\text{eff}}}{T_{\text{eff,0}}}^2.$$  (1)

For solar-type stars, a small error in estimating the effective temperature $T_{\text{eff}}$ would result in a large error in $R/R_\odot$ since

| TABLE 3 | ORBIT SOLUTIONS AND PHYSICAL PARAMETERS: R136-38 |
|-----------------|---------------------------------|-----------------|-----------------|
| **Parameter**   | **System**                       | **Primary**     | **Secondary**   |
| Orbital:        |                                 |                 |                 |
| $P$ (days)      | 3.39 (adopted)                  | ...             | ...             |
| $e$             | 0.00 (adopted)                  | ...             | ...             |
| $T_{\text{primary conjunction (MJD)}}$ | 51,621.40 ± 0.03 | ...             | ...             |
| $y$ (km s$^{-1}$) | ...                            | 278.2 ± 0.4     | 272.3 ± 0.3     |
| $K$ (km s$^{-1}$) | ...                            | 174.7 ± 0.5     | 424.8 ± 0.2     |
| $m_{o}/m_{p}$   | 0.41                            | ...             | ...             |
| $R_1$ (km s$^{-1}$) | ...                            | 2.3             | 20.3            |
| $a \sin i (R_\odot)$ | 40.2                           | 11.7            | 28.5            |
| $m \sin^3 i (M_\odot)$ | ...                           | 53.8 ± 0.2      | 22.1 ± 0.1      |
| Spectral and photometric: |                                 |                 |                 |
| Spectral type   | ...                            | O3 V            | O6 V            |
| $T_{\text{eff}}$ (K) | ...                            | 48,500 ± 4850$^a$ | 42,200 ± 4220$^a$ |
| $\Delta m$      | 1.0 ± 0.2                      | ...             | ...             |
| $M_V$           | -5.3                           | -4.9 ± 0.2$^b$  | -3.9 ± 0.2$^b$  |
| Bolometric correction | ...                            | -4.4 ± 0.3$^a$  | -4.0 ± 0.3$^a$  |
| $M_{\text{bol}}$ | ...                            | -9.3 ± 0.4$^{a,b}$ | -7.9 ± 0.4$^{a,b}$ |
| Radius ($R_\odot$)| ...                            | 9.3 ± 1.0$^{a,b}$ | 6.4 ± 0.7      |
| $r_{\text{rms}}$ | ...                            | 110 ± 12        | 76 ± 9          |
| $a \sin i$      | ...                            | 130 ± 20        | 90 ± 20         |
| Eclipse depths  | ...                            | 0.23            | 0.20            |
| Inclination: geometry (deg) | 79.0 ± 1.0                      | ...             | ...             |
| Inclination: GENSYN model (deg) | 79.0 ± 1.0                      | ...             | ...             |
| Masses:         |                                 |                 |                 |
| $m$, orbit($M_\odot$) | ...                            | 56.9 ± 0.6      | 23.4 ± 0.2      |
| $m$, evolutionary tracks ($M_\odot$) | ...                           | 53 ± 5$^c$      | 29 ± 2$^c$      |

$^a$ Adopting a 10% uncertainty in the spectral type–$T_{\text{eff}}$ relationship.
$^b$ Errors (anticorrelated).
$^c$ Errors on the masses from the evolutionary tracks are based solely on the errors in $M_V$. 
there is such a steep inverse relationship with $T_{\text{eff}}$. However, for hot stars we must make a very large correction for the bolometric correction (BC) in determining $L/L_{\odot}$, starting with $M_V$ and considering that the BC has a very steep dependence on $T_{\text{eff}}$ as well:

$$BC = 27.66 - 6.84 \log T_{\text{eff}} \ ,$$

from Vacca et al. (1996). Thus, substituting this into equation (1) and adopting $T_{\odot} = 5770$ K, we find

$$\frac{R}{R_{\odot}} = 871.67 \times 10^{-M_V/5} T_{\text{eff}}^{-0.632} \ .$$

By propagation of errors we then find that

$$\sigma_{R/R_{\odot}}^2 = \sigma_T^2(-550.90 \times 10^{-M_V/5} T_{\text{eff}}^{-1.632})^2$$

$$+ \sigma_{M_V}^2(-401.42 \times 10^{-M_V/5} T_{\text{eff}}^{-0.632})^2 \ .$$

3.2. R136-38

Six of the 15 spectra showed double lines at H$\gamma$ and He II $\lambda$4542. There is a large magnitude difference between the two components, which we measure as $\Delta m = 1.0 \pm 0.2$ mag. The He I $\lambda$4471 line clearly follows the motion of the secondary but never showed any component due to the primary. Thus, we have a good measurement of the motion of the secondary for both single-lined and double-lined phases. Occasionally, the He I line was too noisy to measure. We find that the single-lined phases follow the motion of the primary very well, but we do not give those any weight in the orbit solutions. The primary is of spectral type O3 V, while the secondary is of spectral type O6 V, as judged by the relative strengths of He I and He II during the double-lined phases. The photometry shows well-pronounced dips of $\sim 0.2$ mag indicative of eclipses.

Period searches on the radial velocity data (both primary and secondary) and on the photometry all revealed the same period of 3.39 days. We present the orbital parameters in Table 3 and show the radial velocity curves and orbit fit in Figure 1. We find that the rotational velocities are consistent with synchronous rotation. Analysis of the light curve finds a well-determined orbital inclination of $i = 79^\circ \pm 1^\circ$. We show the light-curve data and the model fit in Figure 1 as well.

This is a very interesting system, containing stars of extremely high masses, with the O3 V primary having a mass of $57 M_{\odot}$. This is higher than the mass determined from any other binary, exceeding the mass of even that of...
Plaskett’s star (51 \( M_\odot \); Bagnuolo, Gies, & Wiggs 1992).\(^3\) We compare these to the masses derived from the evolutionary tracks in Table 3 and find excellent agreement.

### 3.3. R136-39

This system consists of an O3 V + O5.5 V pair. Of the 15 spectra, 11 showed double lines at H\( \gamma \) and He II \( \lambda 4542 \), and it is clear that He I \( \lambda 4471 \) comes purely from the secondary. The magnitude difference between the two components is 0.45 \( \pm \) 0.1 mag. The period is 4.06 days, as determined from the radial velocities. Inspection of the unphased photometry did not show any obvious signs of an eclipse, but when phased according to the radial velocity information we find that there is poor coverage near the important phases Fig. 2. This allows us to assign only an upper limit on \( i \), and our modeling suggests that the orbital inclination must be less than 75\(^\circ\) to account for the lack of deeper eclipses. This places only lower limits on the masses on the system, of 27 and 21 \( M_\odot \). The line widths are consistent with synchronous rotation.

### 3.4. R136-42

This system consists of an O3 V + O3 V pair. Of the 15 spectra, 11 showed double lines at H\( \gamma \) and He II \( \lambda 4542 \), and there was no trace of He I in any of our spectra. The magnitude difference between the two components is modest, \( \Delta m = 0.2 \pm 0.1 \). The light curve shows a very deep eclipse (0.5 mag), suggesting that we are viewing this system at a very favorable inclination Fig. 3.

A period search of both the radial velocity and photometry data yielded the same value of \( P = 2.89 \) days. We give the orbital parameters in Table 5 and show the orbit and light curve in Figure 3. We find \( i = 85^\circ \). The masses are among the highest seen in a spectroscopic binary: 40 and 33 \( M_\odot \). The line widths are consistent with synchronous rotation.

### 3.5. R136-77

The last system we discuss consists of two O5.5 V + O5.5 V stars with equal brightness. Of the 15 spectra, 12 showed double lines at H\( \gamma \), He I \( \lambda 4471 \), and He II \( \lambda 4542 \). However, since we could not distinguish the primary from the secondary, it was necessary to rely upon the velocity differences between the two components in order to find the period; a period search of the photometry yielded identical results, and strong (0.4 mag) eclipses are evident Fig. 4. The

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\( ^3 \) There are two other contenders for the recorder holder. (1) HD 92740 is a WN7 Wolf-Rayet star in which the absorption lines and emission lines follow the same orbital motion. By combining spectra from six He I lines, Schweickhardt et al. (1999) reported the detection of a secondary absorption spectrum, which they describe as O9 III. The double-lined orbit solution yields a mass of 55.3 \( \pm \) 7.3 \( M_\odot \) for the Wolf-Rayet star. (2) HD 93205 is an O3 V + O8 V pair recently studied by Antokhina et al. (2000). The mass of the O3 V primary was found to be 32–154 \( M_\odot \), with a most probable value of 45 \( M_\odot \). We are indebted to D. Gies for reminding us of these systems.
Orbital:

| Parameter                  | System | Primary | Secondary |
|----------------------------|--------|---------|-----------|
| $P$ (days)                 | 4.06 (adopted) | ... | ... |
| $e$                        | 0.00 (adopted) | ... | ... |
| $T$ primary conjunction (MJD) | 51,620.59 ± 0.01 | ... | ... |
| $\gamma$ (km s$^{-1}$)     | ... | 271.8 ± 0.3 | 262.0 ± 0.3 |
| $K$ (km s$^{-1}$)          | ... | 200.8 ± 0.5 | 266.3 ± 0.4 |
| $m_i/m_j$                  | 0.754 ± 0.002 | ... | ... |
| $R_1$ (km s$^{-1}$)        | ... | 7.1 | 9.5 |
| $a \sin i (R_0)$           | 37.5 | 16.1 | 21.4 |
| $m \sin^3 i (M_\odot)$     | ... | 24.5 ± 0.1 | 18.5 ± 0.1 |

Spectral and photometric:

| Parameter                  | System | Primary | Secondary |
|----------------------------|--------|---------|-----------|
| Spectral type              | O3 V   | O5.5 V  |           |
| $T_{\text{eff}}$ (K)       | 48,500 ± 4850*a | 43,200 ± 4320*a |
| $\Delta m$                | 0.45 ± 0.1 | ... | ... |
| $M_V$                      | -5.2 | -4.7 ± 0.1*b | -4.2 ± 0.1*b |
| Bolometric correction      | ... | -4.4 ± 0.3*a | -4.1 ± 0.3*a |
| $M_{\text{bol}}$           | ... | -9.0 ± 0.3*a,b | -8.3 ± 0.3*a,b |
| Radius ($R_0$)             | ... | 8.1 ± 0.6*a,b | 7.1 ± 0.6 |
| $v_{\text{sync}}$          | ... | 83 ± 6 | 71 ± 6 |
| $v \sin i$                | ... | <100 | <100 |
| Eclipse depths             | ... | <0.05? | ... |
| Inclination: geometry (deg) | <72.0? | ... | ... |
| Inclination: GENSYN model (deg) | <75.0 | ... | ... |

Masses:

$\text{orbital } (M_{\odot})$ ... >27.2 >20.5  
$m_{\text{evolutionary tracks}} (M_{\odot})$ ... 46 ± 2*a 34 ± 2*a

*a Adapting a 10% uncertainty in the spectral type–$T_{\text{eff}}$ relationship.
*b Errors (anti)correlated.
*c Errors on the masses from the evolutionary tracks are based solely on the errors in $M_V$.

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TABLE 4
Orbit Solutions and Physical Parameters: R136-39

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TABLE 5
Orbit Solutions and Physical Parameters R136-42

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*a Adapting a 10% uncertainty in the spectral type–$T_{\text{eff}}$ relationship.
*b Errors (anti)correlated.
*c Errors on the masses from the evolutionary tracks are based solely on the errors in $M_V$. 
period was then used to phase the radial velocity data and assign velocities to one star or the other. We designate the slightly more massive star the primary. The radial velocity data, orbit solution, and light curve are shown in Figure 4. The line widths are again found to be consistent with synchronous rotation.

3.6. Other Light Variables

In doing the photometry, we found five additional stars with significant photometric variations. We show the light curves in Figure 5. R136-07 (Melnick 39), R136-15 (Melnick 30), R136-24 (R136a7), and R136-25 all show signatures of what might well be eclipses. The star R136-08 (Melnick 34) shows a much more puzzling behavior, changing by several tenths of a magnitude over the course of 3 weeks. The variations appear to be periodic. The spectrum of R136-08 mimics that of a Wolf-Rayet star, although Massey & Hunter (1998) argue that it is simply a “super Of” star whose very high luminosity and stellar winds result in a spectrum dominated by emission. Spectroscopic and photometric monitoring of all five of these stars has been proposed for Cycle 11 with HST.

4. DISCUSSION

Our analysis of the four R136 binaries have revealed orbital masses that are among the highest ever directly measured via this simple application of Kepler’s second law. We can use these new data to compare to the masses derived from the evolutionary tracks.⁴ We have included these values in Tables 3, 4, 5, and 6, and we present the Hertzsprung-Russell diagrams (HRDs) in Figure 6. The agreement between the masses derived from these tracks and the actual measured masses is excellent for the three cases with eclipses.

In placing the stars in the HRD, we have chosen to adopt the effective temperature scale of Chlebowski & Garmany (1991). This is similar to the scale given by Conti (1988), who provides a critical discussion and concludes that the absolute (but not relative) uncertainties in the scale are about 10%. Since that time, more modern atmospheric models have been used to analyze a number of O-type stars in the Milky Way, LMC, and SMC; see, e.g., Puls et al. (1996). Such studies led Vacca et al. (1996) to propose a new effective temperature scale, which is ~6% hotter than the Conti (1988) calibration and ~3% hotter than the Chlebowski & Garmany (1991) scale for the spectral types discussed in the current paper. We note that there are no spectral type–to–effective temperature scales determined for stars in the LMC and SMC and that Vacca et al. (1996) restricted their study to Galactic stars. Thus, refinements in the effective temperature scale will change the location of

⁴ We have used the older Schaerer et al. (1993) evolutionary tracks as these were the last set made public by the Geneva group that includes normal (rather than enhanced) mass-loss rates. Newer models including rotation are becoming available, but as yet none with the metallicity appropriate to the LMC. However, we expect that this effect will be small near the ZAMS, as suggested by Fig. 6 in Maeder & Meynet (2001).
Fig. 5.—Light curves for five other suspected binaries. R136-08 (Melnick 34) show gradual variations with a period of 20 days; the others show changes typical of eclipses.

the stars in the HRD, but the error bars in Figure 6 are probably realistic. Note that we have included only the uncertainty in $M_V$ in estimating the errors on the evolutionary track masses in Tables 3–6; were we to include the uncertainty in the effective temperature scale as well, the percentage error would roughly double.

The stars do fall slightly to the left of where we expect in the HRDs. Massey & Hunter (1998) found ages of 1–2 Myr for the R136 cluster, with the larger value corresponding to the cooler effective temperature scale, which we have used here. Yet the components in all four of our binaries lie on or near the ZAMS to higher effective temperatures than the 2 Myr isochrones shown in Figure 6. We do not have a ready explanation for this. We note that all four of these systems are relatively close pairs. Comparison of the orbital separations $a \sin i$ with the stellar radii (both quantities appear in Tables 3–6) reveals that the components are typically separated by $\sim 2$ times the sum of the radii. This is sufficiently close for tidal forces to have played a significant role. We see ready evidence of this in that there must have been some dynamical evolution for the orbits to be circular and the stars to be locked in synchronous rotation.$^5$ Such tidal

$^5$ The time expected for tidal forces to circularize an orbit can be estimated using eq. (2) of Shu & Lubow (1981); adopting parameters appropriate to high-mass stars with convective cores (Zahn 1975, 1977) leads to $\sim 500,000$ yr for these systems.
forces may have affected the evolution of the stars (providing additional heating on the envelopes), and in that case, these systems are not telling us as much as we would like about single stars. It is hoped that some of the stars identified in § 3.6 may provide examples of massive binaries with longer periods.

Such systems would also help determine whether the new generation of rotating stellar models does better than the standard nonrotating models. Maeder & Meynet (2000) have recently invoked rotation to explain the discrepancy in masses between the evolutionary tracks and stellar atmosphere calculations; they note that tracks that fail to include rotation may overestimate the mass by as much as 50% in cases of high rotation and luminosity. The short periods of our binaries have resulted in slow rotation due to tidal forces, leading to little difference in the masses predicted by nonrotating and rotating models.

We are grateful to Abi Saha for extensive discussions of how best to observe variable objects in order to obtain good phase coverage. In order to measure the rotational velocities of the stars, we used the model atmosphere code of Rolf Kudritzki and his collaborators. We thank Deidre Hunter for a critical reading of the manuscript and Andy Odell for an interesting conversation about one of the stars. Kim Venn provided useful suggestions that improved the paper. Support for REU student J. V. was provided by NSF grant 99-88007. HST proposal GO-8217 was provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

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