FUNDAMENTAL PROPERTIES AND DISTANCES OF LARGE MAGELLANIC CLOUD ECLIPSING BINARIES. IV. HV 5936

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ABSTRACT

We have determined the fundamental properties and distance of a fourth eclipsing binary (EB) system in the Large Magellanic Cloud, HV 5936 (B0.5 V + B2 III). As in our previous studies, we combine “classical” EB light-curve and radial velocity curve analyses with modeling of the UV/optical spectral energy distribution of HV 5936 to produce a detailed characterization of the system. In this paper, we also include an analysis of the high-resolution optical absorption line spectra of the binary components. We find HV 5936 to be an Algol-class system, in which the masses of the primary and secondary stars have evolved via mass transfer to their current values of 11.6 and 4.7 $M_{\odot}$, respectively. The properties of the primary star are indistinguishable from those of a “normal” star of the same current mass. The secondary is found to be overluminous for its current mass and exhibits a factor of 2 enhancement in its surface He abundance. These results are compatible with case A mass exchange occurring during the core hydrogen-burning phase of the current secondary. The distance derived to the system, 43.2 ± 1.8 kpc, implies a distance of ~44.3 kpc to the optical center of the LMC. This is several kiloparsecs closer than found in our analyses of other systems, and we suggest that HV 5936 lies “above” the LMC disk. This is supported by the very low interstellar H I column density and low $E(B-V)$ found for the system—both of which are consistent with expected Milky Way foreground material—and may be associated with HV 5936’s location near the LMC supergiant shell LMC 4.

Subject headings: binaries: eclipsing — distance scale — Magellanic Clouds — stars: distances — stars: fundamental parameters — stars: individual (HV 5936)

1. INTRODUCTION

This is the fourth in a series of papers presenting results from detailed analyses of B-type eclipsing binary (EB) systems in the Large Magellanic Cloud (LMC). Our primary scientific goals are (1) to determine an essentially complete description of the stellar properties of each system, thus providing tests and constraints for stellar evolution theory, and (2) to measure precise individual distance for each system, from which the general distance to the LMC can be derived. Because of its role as a fundamental calibrator for distance indicators, the LMC’s distance is particularly important for determining the size scale of the universe, and its current uncertainty of 10%–15% contributes considerably to the uncertainty in the Hubble constant (see, e.g., Mould et al. 2000).

In our previous studies, we examined the LMC EB systems HV 2274 (Guinan et al. 1998, hereafter Paper I; Ribas et al. 2000b), HV 982 (Fitzpatrick et al. 2002, hereafter Paper II), and EROS 1044 (Ribas et al. 2002, hereafter Paper III). The apparent locations of these systems in the LMC can be seen in Figure 1. The results of these analyses are beautifully consistent with expectations from stellar structure theory and provide strong constraints on the distance to the LMC. As discussed in Paper III, the three individual distances are all consistent with a mean of ~48 kpc, although there is a suggestion that HV 982 and, by association, perhaps the general 30 Doradus region, may lie behind the LMC’s “bar” by several kiloparsecs. Conclusions about the LMC’s distance are somewhat dependent on assumptions about its spatial orientation and need to be strengthened with additional measurements from the remaining eclipsing binaries in our program. Our approach is ideally suited to pursuing the issues of the spatial orientation, structure, and general distance to the LMC, since we measure precise distances to individuals systems that are widely spread across the face of the LMC.

In this paper, we apply our analysis to a fourth LMC B-type EB, HV 5936, and derive its stellar properties and distance. This system, with $V \approx 14.8$, stands in some contrast to those in our previous studies in both its composition and its location. HV 5936 is a semidetached system, in which the cooler, less massive component fills completely its Roche lobe. Thus, the currently more massive (and more luminous) component began its life as the junior, lower mass member of the binary. This provides an excellent opportunity to examine the characteristics of the massive component, which—because of the rapid dynamical relaxation expected to follow mass transfer—should be indistinguishable from a “normal” star of the same current mass. In addition to this feature, HV 5936 is located in a very different part of the LMC from our previous targets (see Fig. 1), lying several degrees north of the LMC’s “bar” and superposed on a well-known “hole” in the LMC’s H I distribution (McGee & Milton 1966), corresponding to the
supergiant shell LMC 4 (Meaburn 1980). Its distance should reflect strongly the spatial orientation of the LMC, i.e., its inclination angle and line-of-nodes orientation, and could provide constraints on these factors.

The structure of this paper is similar to that of our earlier works. In § 2 we describe the data included in the study. In § 3 we describe and present the results from our standard analysis, which incorporates the binary’s light curve, radial velocity curve, and UV/optical spectral energy distribution. A study of the high-resolution optical spectrum of the HV 5936 components is presented in § 4. We combine all our results and give a detailed characterization of the properties and likely history of the HV 5936 system in § 5. Some aspects of our results relating to the interstellar medium toward HV 5936 are described in § 6, including an indication of the relative location of HV 5936 within the LMC. Finally, we derive the distance to the system and compare it with our previous results in § 7 and provide some summary comments in § 8.

2. THE DATA

Three distinct data sets are required to carry out our analyses of the LMC EB systems: precise differential photometry (yielding light curves), medium-resolution spectroscopy (yielding radial velocity curves), and multiwavelength spectrophotometry (yielding temperature and reddening information). Each of these three data sets is described briefly below. As in our previous papers, the primary (P) and secondary (S) components of the HV 5936 system are defined photometrically and refer to the hotter and cooler components, respectively.

2.1. Optical Photometry

CCD differential photometric observations of HV 5936 were reported by Jensen, Clausen, & Giménez (1988). These data were obtained between 1983 and 1984 with a 1.54 m telescope at the European Southern Observatory (La Silla, Chile). The published light curves, obtained in the Johnson
B and V passbands, have fairly good phase coverage, with 44 and 144 measurements, respectively. According to Jensen et al., the precision of the individual differential photometric measurements is better than 0.010 mag. In this study, we adopt the orbital ephemeris determined by Jensen et al.:

\[ T(\text{Min I}) = \text{HJD} 2,445,657.7911 + 2.8050681E \]

2.2. Optical Spectroscopy

Radial velocity curves for HV 5936, and a number of other LMC EBs, were derived from optical echelle spectra obtained by us during six- and eight-night observing runs in 2000 January and December, respectively, with the Blanco 4 m telescope at Cerro Tololo Inter-American Observatory in Chile. The seeing conditions during the two runs ranged between 0.7 and 1.8. We secured 18 spectra of HV 5936—near orbital quadratures—covering the wavelength range 3600–5500 Å, with a spectral resolution of \( \lambda / \Delta \lambda \approx 22,000 \), and a signal-to-noise ratio (S/N) of \( \approx 20 : 1 \). The plate scale of the data is 0.08 Å/pixel (5.3 km s\(^{-1}\) pixel\(^{-1}\)), and there are 2.6 pixels per resolution element. Identical instrumental setups were used for both observing runs. The exposure time per spectrum was 1800 s, sufficiently short to avoid significant radial velocity shifts during the integrations. All the HV 5936 observations were bracketed with ThAr comparison spectra for proper wavelength calibration. The raw images were reduced using standard NOAO/IRAF tasks (including bias subtraction, flat-field correction, sky-background subtraction, cosmic-ray removal, extraction of the orders, dispersion correction, merging, and continuum normalization).

A typical spectrum is shown in Figure 2. The H\( \alpha \) Balmer lines and the strongest He\( \text{I} \) features are labeled, with arrows marking the expected line positions for the two components of the system (according to the radial velocity curve solution described in § 3.2). This spectrum was obtained at orbital phase 0.30 and illustrates the clean velocity separation of the two components of the binary.

To determine the radial velocities of HV 5936’s two components from the echelle spectra, we followed the procedure described in Paper II, utilizing the KOREL program (Hadrava 1995, 1997). KOREL is based on the “spectral disentangling” technique, which assumes that an observed double-lined spectrum is a simple linear combination of two single-lined spectra whose velocities reflect the orbital properties of the system. When applied to a set of spectra—obtained over a range of orbital phases—KOREL yields component velocities (relative to the system barycenter) for each individual spectrum and “disentangled” spectra for each of the two binary members, combining information from the whole ensemble of spectra. We applied the KOREL analysis to our echelle data in the 4000–5000 Å wavelength region. The H\( \delta \), H\( \gamma \), and H\( \beta \) lines were excluded by setting the normalized flux to unity in a window around their central wavelength. To translate the velocities to the heliocentric system, we determined the systemic velocity of

![Fig. 2.—Normalized spectrum of HV 5936 near prominent H\( \alpha \) and He\( \text{I} \) lines. The spectrum was obtained with the Blanco 4 m telescope at Cerro Tololo Inter-American Observatory on HJD 2,451,902.7046 at binary phase 0.297. The velocity separation between the primary and secondary stars at this phase is \( \Delta v = 355 \text{ km s}^{-1} \). This figure demonstrates that the absorption lines from the two stars are cleanly resolved and, thus, that the radial velocity measurements will be immune to blending effects.](image-url)
HV 5936 from the individual disentangled spectra. Cross-correlation of these extracted spectra with a high-S/N (~250) observed spectrum (HR 1443; B2 IV–V) and with a synthetic template yielded values consistent with a systemic velocity of \( v_\text{s} = +314.3 \pm 5.8 \text{ km s}^{-1} \).

Table 1 lists the heliocentric radial velocities derived from all the CTIO spectra, using the procedure outlined above ("RV\(_P\)" and "RV\(_S\)"). Also listed are the dates of observation and the corresponding phases. A large number of KOREL runs from different starting points were carried out to explore the parameter space and make realistic estimates of the uncertainties. A detailed discussion of these is left for § 3.2.

The individual disentangled spectra of the primary and secondary provide valuable insight into the nature of the HV 5936 system and a precise measurement of its distance. Each of the interdependent analyses. These involve the radial velocity curve, the light curve, and the spectral energy distribution (SED). The combined results provide essentially a complete description of the gross physical properties of the HV 5936 system and a precise measurement of its distance. Each of the three analyses is described below.

3. THE ANALYSIS

Our study of HV 5936 proceeds from three separate but interdependent analyses. These involve the radial velocity curve, the light curve, and the spectral energy distribution (SED). The combined results provide essentially a complete description of the gross physical properties of the HV 5936 system and a precise measurement of its distance. Each of the three analyses is described below.

### TABLE 1

**Heliocentric Radial Velocity Measurements for HV 5936**

| HJD       | Orbital Phase | RV\(_P\) (km s\(^{-1}\)) | RV\(_S\) (km s\(^{-1}\)) | \((O-C)_P\) (km s\(^{-1}\)) | \((O-C)_S\) (km s\(^{-1}\)) |
|-----------|---------------|---------------------------|---------------------------|----------------------------|----------------------------|
| 51,558.733 | 0.6719        | 411.2                     | 84.6                      | 1.8                        | 2.0                        |
| 51,558.760 | 0.6812        | 413.7                     | 77.5                      | 1.5                        | 1.3                        |
| 51,560.740 | 0.3871        | 240.4                     | 486.6                     | −1.9                       | −6.2                       |
| 51,560.769 | 0.3963        | 246.8                     | 475.4                     | −0.3                       | −5.8                       |
| 51,561.684 | 0.7239        | 421.1                     | 55.8                      | −0.2                       | −1.1                       |
| 51,561.707 | 0.7318        | 421.6                     | 53.5                      | −0.5                       | −1.6                       |
| 51,562.774 | 0.1122        | 245.7                     | 484.5                     | 1.3                        | 1.0                        |
| 51,562.790 | 0.1189        | 240.6                     | 490.5                     | −0.3                       | −1.2                       |
| 51,895.767 | 0.8234        | 412.8                     | 76.3                      | 0.2                        | −1.3                       |
| 51,895.790 | 0.8317        | 408.4                     | 81.2                      | −1.6                       | −2.4                       |
| 51,898.638 | 0.8470        | 402.7                     | 96.0                      | −1.9                       | 0.0                        |
| 51,898.661 | 0.8553        | 402.7                     | 102.1                     | 1.3                        | −1.6                       |
| 51,899.632 | 0.2014        | 211.9                     | 565.6                     | 1.1                        | 2.8                        |
| 51,899.784 | 0.2556        | 206.5                     | 578.1                     | 1.0                        | 3.0                        |
| 51,900.806 | 0.6199        | 387.3                     | 133.8                     | −0.3                       | 1.3                        |
| 51,900.829 | 0.6281        | 391.9                     | 127.4                     | 0.2                        | 4.5                        |
| 51,901.632 | 0.2882        | 207.6                     | 569.7                     | −0.7                       | 0.4                        |
| 51,902.704 | 0.2966        | 209.6                     | 568.0                     | −0.2                       | 1.8                        |

### TABLE 2

**HST Spectrophotometric Observations of HV 5936**

| Instrument | Detector | Data Set Name | Date of Observation | Orbital Phase | \( k_P \) \(^a\) | \( k_S \) \(^b\) |
|------------|----------|---------------|---------------------|---------------|----------------|----------------|
| FOS......... | G130H     | Y3FU0803T     | 1997 Jan 31         | 0.115         | 1.0059         | 0.9875         |
|            | G190H     | Y3FU0806T     | 1997 Jan 31         | 0.137         | 1.0116         | 1.0151         |
|            | G270H     | Y3FU0808T     | 1997 Jan 31         | 0.133         | 1.0106         | 1.0101         |
|            | G400H     | Y3FU0804T     | 1997 Jan 31         | 0.128         | 1.0093         | 1.0038         |
| STIS........ | G430L     | O665B6030     | 2001 Apr 22         | 0.654         | 1.0491         | 1.0360         |
|            | G750L     | O665B6040     | 2001 Apr 22         | 0.657         | 1.0490         | 1.0396         |

\(^a\) The quantities \( k_P \) and \( k_S \) are corrections used in the spectral energy distribution analysis to account for out-of-eclipse light variations in the HV 5936 system due to reflection effects and gravitational distortion of the secondary. See § 3.3.
3.1. The Light Curve

The fits to the light curves were carried out using an improved version of the Wilson-Devinney (W-D) program (Wilson & Devinney 1971) that includes a model atmosphere routine developed by Milone, Stagg, & Kurucz (1992) for the computation of the stellar radiative parameters. Both detailed reflection-model (MREF = 2, NREF = 1) and proximity-effect corrections were taken into account when fitting the light curves. The bolometric albedo and the gravity-brightening coefficients were both set at the canonical value of 1.0 for stars with radiative envelopes. For the limb darkening we used a logarithmic law as defined in Klinglesmith & Sobieski (1970), with first- and second-order coefficients interpolated at each iteration for the exact \( T_{\text{eff}} \) and \( \log g \) of each component from a set of tables computed in advance using a grid of ATLAS9 model atmospheres. A mass ratio of \( q = M_S/M_P = 0.407 \) was adopted from the spectroscopic solution (§3.2), and the temperature of the primary component was set to \( T_{\text{eff}}^P = 26,450 \) K, as discussed in §3.3. We have adopted a circular orbit, as suggested by the equal width of the eclipses and the occurrence of the secondary eclipse at exactly phase 0.5. Further support for this comes from the fact that the system is semidetached (see below) and orbital circularization takes place over a very short timescale. Finally, the rotational velocity of the primary star was set to 1.25 times the synchronous rate, and the secondary star was assumed to rotate synchronously. A discussion of the component’s rotational velocities is provided in §4.

Our initial light-curve fits were run with a detached configuration (W-D mode 2). However, preliminary tests indicated a rapid decrease of the surface gravitational potential of the secondary component until reaching its critical value. Several runs from different starting values confirmed this behavior. Therefore, all further W-D solutions were run in mode 5, i.e., the secondary component filling its Roche critical surface. According to this, HV 5936 is a semidetached binary in which the cooler, less massive component appears to be more evolved and fills its Roche lobe. This is the classical configuration of post–mass transfer Algol-class systems.

In our final analysis we solved for the following light-curve parameters: the orbital inclination \( (i) \), the temperature of the secondary \( (T_{\text{eff}}^S) \), the gravitational potential of the primary \( (\beta_P) \), the luminosity of the primary \( (L_P) \), and a phase offset \( (\delta \phi) \) that accounts for possible inaccuracy in the adopted ephemeris reference epoch. The iterations with the W-D code were carried out automatically until convergence, and a solution was defined as the set of parameters for which the differential corrections suggested by the program were smaller than the internal probable errors on three consecutive iterations. As a general rule, several runs with different starting parameters are used to make realistic estimates of the uncertainties and to test the uniqueness of the solution.

Because of the relatively small number of free parameters and the constraint provided by the semidetached configuration, convergence was achieved rapidly in the light-curve fits. The rms residuals were determined to be 0.010 and 0.009 mag for the \( B \) and \( V \) light curves, respectively. These values are approximately equal to the observed scatter of the observations. The resulting orbital and physical parameters are well defined, and the best-fitting model light curves, together with the \( O-C \) residuals, are shown in Figure 3. As can be seen in the figure, a small systematic departure of the fit arises in the first quadrature (phase 0.2–0.4) of the \( V \) light curve. This cannot be confirmed in the \( B \) light curve because of the lack of photometric coverage. It is uncertain at this point whether this is a real effect or just an artifact of the photometric reduction. If it were real, the asymmetry of the quadrature maxima could arise from the presence of a hot spot on the primary component. This is not unexpected in an Algol system, because active mass transfer could be taking place and a hot spot in the atmosphere of the hotter component might arise from the impact of the accreting material and subsequent kinetic heating. We explored this scenario by running W-D solutions with an area on the primary component 10% hotter than the rest of the atmosphere. The systematic trend in the residuals did indeed disappear when the spot was included, but this is not surprising because we added two new free parameters in the analysis (spot radius and location). The new rms residuals were found to be 0.009 and 0.008 mag for the \( B \) and \( V \) light curves, respectively. The solution with the hot spot is very similar, but yields a radius for the primary component about 2% smaller and a temperature ratio about 5% larger.

In the absence of conclusive evidence, we decided to adopt the “ unperturbed ” solution without a hot spot. Besides, the resulting spot location is not consistent with the expected impact site of a putative stream of matter using the model of Lubow & Shu (1975). (Note that the fractional

\[ \text{Note that the surface gravitational potential of the secondary is constrained by the semidetached condition.} \]
As is evident from Figure 3, the light curves of HV 5936 display rather prominent out-of-eclipse variability. This arises chiefly from variations in the effective radiating area of the secondary star. Because of its nonspherical shape (filling its Roche lobe), the surface area of the secondary star changes with the orbital phase, and so does its total brightness. The stellar cross section reaches a maximum at the orbital quadratures and a minimum at the eclipses. Another factor contributing to the out-of-eclipse variation is irradiation. This is a rather significant effect in Algols, because the secondary star is often larger but cooler than the primary. Thus, when the primary component is in front (near the phase of the secondary eclipse), we see its light reflected off the atmosphere of the secondary star. This causes the ingress and egress of the secondary eclipse to be brighter than the ingress and egress of the primary eclipse. Both effects discussed here are fully accounted for by the physical model on which W-D is based, as proved by the excellent fit to the light curves.

The final orbital and stellar parameters adopted from the light-curve analysis are listed in Table 3. The uncertainties given in this table were adopted not from the formal probable errors provided by the W-D code, but instead from numerical simulations and other considerations. Several sets of starting parameters were tried in order to explore the full extent of the parameter space. In addition, the W-D iterations were not stopped after a solution was found; instead, the program was kept running to test the stability of the solution and the geometry of the $\chi^2$ function near the minimum. The scatter in the resulting parameters from numerous additional solutions yielded estimated uncertainties that we consider to be more realistic and are generally several times larger than the internal statistical errors.

As an internal consistency check, we reanalyzed the light curves with the mass ratio $q$ left as a free parameter, rather than fixing it to the spectroscopically determined value. This test yielded a “photometric mass ratio” of $q_{\text{phot}} = 0.417 \pm 0.031$, which is in excellent agreement with the spectroscopic result of $q = 0.407 \pm 0.016$ (see § 3.2). Photometric estimates of $q$ are strongly dependent on out-of-eclipse light variations, which, in the case of HV 5936, arise primarily from the changing aspects of the tidally distorted stars (as well as the reflection effect). The good agreement of $q_{\text{phot}}$ with the directly determined spectroscopic mass ratio indicates that the light curves are essentially free of significant perturbing effects from gas flows and accretion heating—consistent with our conclusion above from examining the residuals to the light-curve fits. This agreement reaffirms that the orbital and stellar properties determined from the combined solutions of light and radial velocity curves are both self-consistent and robust.

The same light curves as analyzed here (i.e., those from Jensen et al. 1988) have also been studied by Bell et al. (1993). Those authors employed two different light-curve synthesis programs, one of which was a 1983 version of the W-D code. Their solutions were run with a mass ratio quite different from ours ($q_{\text{Bell}} = 0.46$), and this resulted in a larger fractional radius for the secondary component than we find. Also, their adopted temperature for the primary was about 3000 K larger than our value. Apart from those, the rest of the light-curve parameters obtained by Bell et al. are compatible with the ones listed in Table 3. It should be mentioned, however, that our fits display significantly smaller residuals, which probably result from a better-determined mass ratio and the more sophisticated fitting program that we have employed.

### 3.2. The Radial Velocity Curve

The radial velocity curve was fitted using the same version of the W-D program as described above. The free parameters were the orbital semimajor axis ($a$), the mass ratio ($q$), and a velocity zero point (the systemic radial velocity $v_\text{s}$). The rest of the parameters were set to those resulting from the light-curve solutions discussed in § 3.1. The best fit to the radial velocity curve is shown in Figure 4. The fit residuals correspond to rms internal errors of 1.2 and 2.8 km s$^{-1}$ for the primary and secondary components, respectively. The relatively large difference between these residuals is a consequence of the secondary star being significantly less luminous, and thus its velocities have intrinsically larger errors.

The parameters resulting from the radial velocity curve fit are listed in Table 3. The uncertainties given in the table are not taken directly from the W-D output, since they fail to account for any systematic effects that could be present in the velocity data. Instead, we estimated more realistic errors by considering the scatter of the velocities derived from the

### TABLE 3

| Parameter | Value |
|-----------|-------|
| Period    | 2.8050681 ± 0.0000015 days |
| Eccentricity | 0.0 (fixed) |
| Inclination | 80.0 ± 0.2 |
| $T_{\text{eff}}$ | 0.666 ± 0.008 |
| $(L_2/L_1)_{\text{eff}}$ | 0.592 ± 0.011 |
| $(L_2/L_1)_{\text{eff}}$ | 0.629 ± 0.012 |
| $v_\text{p}$ | 0.2708 ± 0.0008 |
| $r_\text{p}$ | 0.3053 ± 0.0034 |
| $\Omega_\text{p}$ | 4.14 ± 0.15 |
| $\Omega_\text{p}$ | 2.69 ± 0.04 |
| $\Delta$ | 0.0006 ± 0.0005 |

**Radial Velocity Curve Analysis**

| Parameter | Value |
|-----------|-------|
| $K_\text{p}$ | 109.1 ± 3.2 km s$^{-1}$ |
| $K_\text{s}$ | 268.2 ± 7.5 km s$^{-1}$ |
| $a$ | 0.407 ± 0.016 |
| $v_\text{s}$ | 314.3 ± 5.8 km s$^{-1}$ |
| $a$ | 21.23 ± 0.46 R$_\odot$ |

**Energy Distribution Analysis**

| Parameter | Value |
|-----------|-------|
| $T_{\text{eff}}$ | 26.450 ± 250 K |
| $[m/H]$ | $-0.63$ ± 0.05 |
| $v_\text{micro}$ | 2.6 ± 0.6 km s$^{-1}$ |
| $E(B-V)$ | 0.047 ± 0.005 mag |
| $\log(R_\text{p}/d)$ | $-23.046$ ± 0.006 |

- Fractional stellar radius $r = R/a$, where $R$ is the stellar "volume radius" and $a$ is the orbital semimajor axis.
- Normalized potential at stellar surface.
- Mass ratio $M_2/M_1$.
- This parameter is assumed to have identical values for both components.
are not a product of the radial velocity curve analysis. The residuals to the continuity due to the partial eclipse of a rotating star (the Rossiter effect), Table 1. Note that the details of the model curve, including the sharp discontinuity due to the partial eclipse of a rotating star (the Rossiter effect), are not a product of the radial velocity curve analysis. The residuals to the fit are shown in the top panel.

Fig. 4.—Radial velocity data for HV 5936 (see Table 2) superposed with best-fitting model. The parameters derived from the data are listed in Table 1. Note that the details of the model curve, including the sharp discontinuity due to the partial eclipse of a rotating star (the Rossiter effect), are not a product of the radial velocity curve analysis. The residuals to the fit are shown in the top panel.

3.3. The UV/Optical Energy Distribution

3.3.1. The Basics

In general, the observed SED \( f_{\lambda0} \) of a binary system can be expressed as

\[
f_{\lambda0} = \left( \frac{R_P}{d} \right)^2 \left[ F_P^{\lambda} + (R_S/R_P)^2 F_S^{\lambda} \right]
\times 10^{-0.4(E(B-V))/k(\lambda-V)+R(V)}.
\]

where \( F_{i}^{\lambda} \) \( i = P, S \) are the surface fluxes of the primary and secondary stars, the \( R_i \) are the absolute radii of the components, and \( d \) is the distance to the binary. The last term carries the extinction information, including \( E(B-V) \), the normalized extinction curve \( k(\lambda-V) = E(\lambda-V)/E(B-V) \), and the ratio of selective to total extinction in the \( V \) band \( R(V) = A(V)/E(B-V) \). In our studies, we represent the stellar surface fluxes with R. L. Kurucz’s ATLAS9 atmospheres and use a parameterized representation of UV-through-IR extinction based on the work of Fitzpatrick & Massa (1990) and Fitzpatrick (1999, hereafter F99). The Kurucz models are each functions of four parameters (\( T_{\text{eff}}, \log g, [m/H] \), and microturbulence velocity \( v_{\text{micro}} \), and the extinction curves are functions of six parameters (see F99). Note that, for the purposes of equation (1), it does not matter which star in a system is identified as the primary.

Following Fitzpatrick & Massa (1999, hereafter FM99), we model the observed SED by performing a nonlinear least-squares fit to determine the best-fit values of all parameters that contribute to the right-hand side of equation (1). For HV 5936 and as for our previous studies, we can make several simplifications that reduce the number of free parameters in the problem: (1) the temperature ratio of the two stars is known from the light-curve analysis; (2) the surface gravities can be determined by combining results from the light- and radial velocity curve analyses and are \( \log g = 3.98 \) and 3.49 for the primary and secondary stars, respectively (see § 5); (3) the values of \([m/H]\) and \( v_{\text{micro}} \) can be assumed to be identical for both components; (4) the ratio \( R_S/R_P \) is known; and (5) the standard mean value of \( R(V) = 3.1 \) found for the Milky Way can reasonably be assumed, given the existing LMC measurements (see, e.g., Koornneef 1982; Morgan & Nandy 1982; also see § 6).

We prepared the spectrophotometric data sets for the SED analysis by (1) velocity-shifting to bring the centroids of the stellar features to rest velocity, (2) correcting for the presence of a strong interstellar H\,I Ly\,$\alpha$ absorption feature in the FOS spectrum at 1215.7 Å (see § 6), and (3) binning to match the ATLAS9 wavelength grid. The statistical errors assigned to each bin were computed from the statistical errors of the original data, i.e., \( \sigma_{\text{stat}}^2 = \frac{1}{\text{N}} \left( \frac{1}{\sigma_i^2} \right) \), where the \( \sigma_i \) are the statistical errors of the individual spectrophotometric data points within a bin. For all the spectra, these binned uncertainties typically lie in the range 0.5%–1.5% of the binned fluxes. The weighting factor for each bin in the least-squares procedure is given by \( w_{\text{bin}} = 1/\sigma_{\text{stat}}^2 \). We exclude a number of individual bins from the fit (i.e., set the weight to zero) for the reasons discussed by FM99 (mainly because of the presence of interstellar gas absorption features).

As discussed in Paper II, we do not merge the FOS and STIS data into a single spectrum, but rather perform the fit on the three binned spectra simultaneously and independently. We assume that the FOS fluxes represent the ‘‘true’’ flux levels and account for zero-point uncertainties in the STIS data by incorporating two zero-point corrections (one for each STIS spectrum) in the fitting procedure. We later explicitly determine the uncertainties in the results introduced by zero-point uncertainties in FOS.

3.3.2. Special Considerations for HV 5936

As noted in § 2.1, the out-of-eclipse variations seen in HV 5936’s light curve result primarily from changes in the
apparent size (i.e., as presented toward the Earth) of the secondary due to its mild nonsphericity and also from phase-modulated reflection of light from the primary off the secondary. These effects must be taken into account in the SED analysis, because they affect the relative contributions of primary and secondary light to the observed SED.

We incorporate the effects through a simple modification of equation (1):

\[ f_\lambda = \left(\frac{R_p}{d}\right)^2 [k_p F_\lambda^p + k_s (R_s/R_p)^2 F_\lambda^s] \times 10^{-0.4(E(B-V)k_0 - V) + R(V)} \]

(2)

where \( k_p \) and \( k_s \) are phase-dependent correction factors accounting for additional reflected light from the primary and the varying apparent size of the secondary, respectively. The values of \( k_p \) and \( k_s \) for each of the spectrophotometric observations are listed in Table 2 and were computed from the results of the W-D light-curve analysis. The \( k_p \) are always greater than 1, since reflection always adds otherwise unseen light from the primary. The value of \( k_s \) for the FOS/G130H spectrum indicates that, at the phase of this observation, the apparent size of the secondary was slightly smaller than its mean value (as given by the volume radius computed by the W-D program). For all the other spectra, the apparent size of the secondary was larger than its mean value. Note that all the corrections for the FOS data sets—which provide the photometric zero point for the SED analysis—are very close to 1.0.

3.3.3. Results

We computed the final fit to HV 5936’s SED, utilizing equation (2) with the appropriate values of \( k_p \) and \( k_s \) inserted for each data set. As in previous papers, we adjusted the weights in the fitting procedure to yield a final value of \( \chi^2 = 1 \)—since the statistical errors of the data underrepresent the total uncertainties (see the discussion in Paper II). This was accomplished by quadratically adding an uncertainty equivalent to 1.9% of the local binned flux to the statistical uncertainty of each flux point. (Essentially identical results occur if the statistical errors are simply scaled by a factor of 2.2 to yield \( \chi^2 = 1 \).) This value of 1.9% gives an indication of the general quality of the fit to HV 5936’s SED, excluding the effect of statistical noise. It is comparable the quality level we have seen in the previous analyses.

The best-fitting values of the energy distribution parameters for HV 5936 and their associated 1 \( \sigma \) uncertainties (“internal errors”) are listed in Tables 3 (stellar properties), 4 (STIS offsets), and 5 (extinction curve parameters). A comparison between the observed spectra and the best-fitting model is shown in Figure 5. The three binned spectra are plotted separately in the figure for clarity (small filled circles). The zero-point offset corrections (see Table 4) were applied to all STIS spectra in Figure 5. Note that we show the quantity \( f_{\lambda 0} \) as the ordinate in Figure 5 (rather than \( f_\lambda \)) strictly for plotting purposes, to “flatten out” the energy distributions.

The correction factors of 10.2% and 5.9% required to rectify the STIS G430L and G750L spectra, respectively, are similar to the results found in Papers II and III. This apparently systematic effect probably results from small light losses in the STIS 0".5 slit. This will be tested by using a wider slit in future STIS observations.

4. SUPPLEMENTAL ANALYSIS OF THE DISENTANGLED SPECTRA

In § 2.2, we utilized the KOREL program primarily to determine the radial velocities of HV 5936’s component stars. However, by-products of this program, i.e., a high-resolution, disentangled optical spectrum for each star, can provide valuable additional information on the binary system that is entirely independent of the analysis described in § 3. This information can be tapped by modeling these absorption-line spectra with synthetic spectra. The potential value of such an analysis is threefold, since it can (1) add new information on the system, (2) independently verify results of the preceding analysis, and (3) identify problems with the preceding analysis.

The disentangled spectra of HV 5936’s two components, as produced by the KOREL program, are shown in Figures 6 and 7. Each spectrum has a resolution of \(-0.2 \, \text{Å} \) and consists of 12,453 data points. The most prominent features in both are lines of H i and He i. The strong C ii λ4267 and Si ii λ4553, 4568, 4574 lines are noted in the primary’s spectrum (Fig. 6). Virtually all the other, weaker absorption features in that spectrum are due to lines of O ii. There are no positive identifications of individual metal absorption lines in the noisier spectrum of the secondary. The ripple-like structure in the range 4140–4170 Å of both spectra (near the position of a He i line) is an artifact of the KOREL program and results because the observations were mainly obtained near orbital quadratures and not distributed more uniformly throughout the orbit. The strengths of all the lines in these two spectra are diluted by the presence of continuum light from both binary components. Given the phase distribution of the original optical data (see Table 1), we compute

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**Table 4**

| STIS Detector | Data Set Name | Offset (FOS – STIS) (%) |
|---------------|---------------|------------------------|
| G430L         | O665B6030     | +10.2 ± 0.5            |
| G750L         | O665B6040     | +5.9 ± 0.7             |

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**Table 5**

| Parameter | Description                           | Value       |
|-----------|---------------------------------------|-------------|
| \( x_0 \) | UV bump centroid (\( \mu \text{m} \)) | 4.55 ± 0.03 |
| \( y \)  | UV bump FWHM (\( \mu \text{m} \))     | 0.59 ± 0.18 |
| \( c_1 \) | Linear offset                         | -1.01 ± 0.40|
| \( c_2 \) | Linear slope                          | 1.02 ± 0.10 |
| \( c_3 \) | UV bump strength                       | 0.53 ± 0.26 |
| \( c_4 \) | FUV curvature                         | 0.61 ± 0.12 |
| \( R(V) \) | FUV curvature                         | 3.1 (assumed) |

Note.—The extinction curve parameterization scheme is based on the work of Fitzpatrick & Massa 1990, and the complete UV-through-IR curve is constructed following the recipe of F99.
that the primary and secondary contribute 63.9% and 36.1%, respectively, of the continuum light in these mean spectra. These values incorporate the reflection and ellipticity effects noted in §3 and have uncertainties of order of \( \pm 1\% \). In Figures 6 and 7, we have adjusted the vertical axes so that the lines are in their correct strengths relative to the bottom of each panel.

We model the disentangled spectra by utilizing ATLAS9 atmospheric structure models, Ivan Hubeny’s spectral synthesis program SYNSPEC, and essentially the same \( \chi^2 \) minimization technique as described in §3.5 for the SED analysis. In general, finding the best-fitting synthetic spectrum for these stars requires the determination of seven parameters. Four of these—\( T_{\text{eff}} \), \( \log g \), [\( m/H \)], and \( \epsilon_{\text{micro}} \)—are required to specify the appropriate ATLAS9 model. Two more—\( v_{\text{radial}} \) and \( v \sin i \) (along with \( \epsilon_{\text{micro}} \))—are used explicitly by SYNSPEC in determining line positions and widths. A final parameter, which we characterize as the percent contribution of each star to the observed continuum, is required to reproduce the dilution of the line strengths. For the case of the HV 5936 stars, we found that the microturbulence velocity was poorly determined, and so we simply adopted the value of 2.6 km s\(^{-1}\) derived in the SED analysis in §3.3. In addition, we simultaneously determined the coefficients of a high-order Legendre polynomial to allow the smoothing out of “bumps and wiggles” that can be seen in the spectra of both stars. These result from deficiencies in the normalization of the original echelle spectra used by KOREL. The 4140–4170 Å region, noted above, was excluded from all fits.

When analyzing the primary’s spectrum, we found that the results of the fitting procedure depended somewhat on the assumed order of the normalizing function. Therefore, we performed seven independent fits, utilizing 10, 15, 20, 25, 30, 35, and 40 order Legendre polynomials. These sample the reasonable range, since a polynomial with fewer than 10 orders cannot match the observed structure in the continuum, while those with more than 40 orders have too much freedom and can distort the observed features. The results of these fits are given in column (2) of Table 6, where we list the simple means of the parameters derived from the seven fits. The uncertainties quoted in the table are the quadratic sum of the internal uncertainties in a single fit and the standard deviation of the ensemble of seven fits. In Figure 6, we show the best-fitting model, corresponding to the case with a 20 order Legendre normalizing function (solid curve). The polynomial itself is shown by the dotted curve. The results from this particular fit are very close to the ensemble averages in Table 6.

The fit to the primary’s disentangled spectrum is very good. The results for \( T_{\text{eff}} \), [\( m/H \)], and the contribution factor are all consistent at the 1 \( \sigma \) level with previous determinations (26,450 K, \(-0.63\), and 63.9\%, respectively). The value of \( \log g \) is 0.12 dex (\(-2.2\) \( \sigma \)) higher than that determined from the binary analysis. However, this is not a large discrepancy and, since the gravity determination depends on the wings of the Balmer lines, we suspect that it arises from deficiencies in the normalization of the original echelle spectra. It is interesting that the metallicity determined here—which mainly reflects weak but numerous lines of O—agrees so well with that derived by the SED analysis—based mainly on Fe and \( m \) absorption in the UV. These two results present a very consistent picture of a general factor of 4 metal underabundance for HV 5936. Note that all of the fits to the primary’s spectrum assume a helium abundance of \( n(\text{He})/n(\text{H}) = 0.084 \), which is based on the observed metal abundance and standard chemical enrichment laws (see §5) and corresponds to a helium mass fraction of \( Y = 0.25 \).

Fits to the secondary’s spectrum were performed in a similar manner as above, except that—since the optical metal lines are all too weak to allow a meaningful determination of [\( m/H \)]—we fixed its value to [\( m/H \)] = \(-0.63\), as derived in §3. Also, we found that the 10 order Legendre fit was inadequate to model the continuum undulations, and so we base our results on six fits with normalization polynomials of 15, 20, 25, 30, 35, and 40 orders. The resulting mean parameters and 1 \( \sigma \) uncertainties from these fits are listed in column (3) of Table 6. These results are much less satisfying than those for the primary. \( T_{\text{eff}} \), \( \log g \), and the contribution factor all differ greatly from the previously determined values (17,600 K, 3.49, and 36.1\%, respectively). In addition,
the value of $v \sin i$ appears inconsistent with the virtually unavoidable requirement that the secondary’s rotation be tidally locked to its orbit (see § 5).

From detailed examination of the fits to the secondary, we found that the discrepancies arise essentially because the secondary’s He i lines are too strong to be well fitted with the temperature of 17,600 K inferred earlier in § 3. It is not likely, however, that the secondary can be significantly hotter than this, since this temperature results from a very well-determined, eclipse-based temperature ratio and an apparently well-determined primary star temperature. Rather, we suggest that the secondary’s He i lines are enhanced in strength arising from a modest enhancement in the He surface abundance. The viability of this suggestion is demonstrated by case II in column (4) of Table 6. The mean parameters and 1 $\sigma$ uncertainties were derived in an identical manner to those in case I, except that the helium abundance was approximately doubled to a value of $n(\text{He})/n(\text{H}) = 0.16$. In addition, the abundances of C and O were depleted by a factor of 10, compared to the base metallicity of $[m/H] = -0.626$, and N was enhanced by a factor of 70. These factors are based on stellar interior models, which are discussed in § 5. It is clear that these adjustments to the elemental abundances yield results completely consistent with the previous measurements of $T_{\text{eff}}$ and $\log g$ for the secondary and the known value of the continuum contribution factor. In addition, the value of $v \sin i$ is well determined and consistent with synchronous rotation (see § 5). In Figure 7, we show the best-fitting model, corresponding to case II with a 25 order Legendre polynomial in Table 6 and includes an enhanced He abundance and modified CNO abundances. It reproduces the stellar properties derived independently in § 3. The asterisks indicate the locations of the strongest features of N ii. See the discussion in § 5 for more information.
TABLE 6
ANALYSIS OF DISENTANGLED SPECTRA OF HV 5936 COMPONENTS

| Stellar Property (1) | Primary Star (2) | Secondary Case I (3) | Secondary Case II (4) |
|----------------------|------------------|----------------------|-----------------------|
| n(He)/n(H)           | 0.084            | 0.084                | 0.16                  |
| T\(_{\text{eff}}\) (K) | 26,900 ± 370     | 21,040 ± 590         | 17,620 ± 250          |
| log \(g\) (cgs)      | 4.11 ± 0.04      | 3.73 ± 0.10          | 3.54 ± 0.06           |
| [m/H]                | −0.60 ± 0.04     | −0.63                | −0.63                |
| \(v_{\text{micro}}\) (km s\(^{-1}\)) | 2.6             | 2.6                  | 2.6                   |
| \(v\sin i\) (km s\(^{-1}\)) | 127.8 ± 1.6     | 139.0 ± 5.4          | 127.0 ± 2.2           |
| \(v_{\text{radial}}\) (km s\(^{-1}\)) | 314.5 ± 1.2     | 318.0 ± 1.8          | 316.7 ± 1.7           |
| Contribution to light (\%) | 62.3 ± 1.3     | 40.5 ± 1.2           | 36.7 ± 0.4            |

\(^a\) Assumed, from the discussion in § 5; corresponds to \(Y = 0.25\).
\(^b\) Enhanced He abundance. Also, the abundances of C, N, and O were adjusted by factors of 0.1, 70, and 0.1, respectively, relative to the base metallicity of \([m/H] = −0.63\). See the discussions in §§ 4 and 5.
\(^c\) There are insufficient spectral features to measure \([m/H]\) from the optical spectrum of the secondary. The value of \([m/H]\) derived from the SED analysis in § 3.3 is assumed.
\(^d\) The microturbulence velocity cannot be measured with the existing data. The value derived from the SED analysis in § 3.3 is assumed.
\(^e\) Contribution factors for the primary and secondary stars were determined independently of each other. They were not constrained to add up to 100%.

Examination of Figure 9 and Table 7 suggests a paradox, in that the more evolved star (i.e., farther from the ZAMS) is the less massive component of the pair. The most plausible explanation for this scenario is that HV 5936 is a

5. THE HISTORY AND NATURE OF THE HV 5936 BINARY SYSTEM

We summarize the basic physical properties of the HV 5936 system in Table 7. The notes to the table indicate how the individual stellar properties were derived from the results of the preceding sections. A scale model of the system is shown in Figure 8. The locations of the HV 5936 components in the log \(T_{\text{eff}}\) versus log \(L\) diagram are shown in Figure 9, where the skewed rectangular boxes indicate the 1 \(\sigma\) error loci (recall that errors in \(T_{\text{eff}}\) and \(L\) are correlated). The position of the zero-age main sequence (ZAMS) is indicated in Figure 9 by the thick curve; the theoretical evolution tracks shown on the figure are discussed below.

TABLE 7
PHYSICAL PROPERTIES OF THE HV 5936 SYSTEM

| Property | Primary Star | Secondary Star |
|----------|--------------|----------------|
| Spectral type \(^a\) | B0.5 V | B2 III |
| Mass \(^b\) (M\(_{\odot}\)) | 11.6 ± 0.5 | 4.7 ± 0.2 |
| Radius \(^c\) (R\(_{\odot}\)) | 5.75 ± 0.23 | 6.48 ± 0.16 |
| log \(g\) (cgs) | 3.984 ± 0.039 | 3.488 ± 0.029 |
| \(T_{\text{eff}}\) (K) | 26,450 ± 250 | 17,600 ± 330 |
| log \((L/L_{\odot})\) \(^d\) | 3.98 ± 0.04 | 3.49 ± 0.03 |
| \([m/H]\) \(^h\) | −0.62 ± 0.05 | −0.62 ± 0.05 |
| \(n(\text{He})/n(H)\) \(^b\) | 0.084 | 0.16 |
| \(v\sin i\) (km s\(^{-1}\)) | 127.8 ± 1.6 | 127.0 ± 2.2 |
| \(v_{\text{sync}}\sin i\) (km s\(^{-1}\)) | 103.1 ± 4.1 | 123.9 ± 2.9 |
| \(d_{\text{HV 5936}}\) (kpc) | 43.2 ± 1.8 |

\(^a\) Estimated from \(T_{\text{eff}}\) and log \(g\).
\(^b\) From the mass ratio \(q\) and the application of Kepler’s third law.
\(^c\) Computed from the relative radii \(r_P\) and \(r_S\) and the orbital semimajor axis \(a\).
\(^d\) Computed from \(g = GM/R^2\).
\(^e\) Direct result of the spectrophotometry analysis and photometrically determined temperature ratio.
\(^f\) Computed from \(L = 4\pi R^2\sigma T_{\text{eff}}^4\).
\(^g\) Mean result from the SED analysis in § 3.3 and the synthetic spectrum analysis for the primary in § 5. For the secondary, abundance anomalies in CNO abundances would be expected, given the observed He enhancement.
\(^h\) For the primary, this corresponds to a He mass fraction of \(Y = 0.25\) and is based on the observed metallicity and standard chemical enrichment. See § 5. For the secondary, \(n(\text{He})/n(H)\) is based on analysis of optical spectra in § 4. The He enhancement is likely accompanied by modifications in the surface abundances of CNO. See § 5.

\(^i\) Measured from the disentangled spectra of the two components as described in § 5.
\(^j\) Theoretical synchronization velocities.
\(^k\) Using \((R_P/d)^2\) from the spectrophotometry analysis and \(R_P\) from the light-curve and radial velocity curve analyses. See § 7.
The post–mass transfer system, as commonly argued to explain the so-called Algol paradox. The originally more massive star evolved beyond the Roche critical surface at a certain point, and some fraction of its mass was transferred to its companion. After that process, the mass-accreting component became more massive than the mass donor, and this is the current status of the system.

In contrast with our previous studies, the strong interaction between the system components prevents us from using evolutionary models to perform a critical self-consistency check of the results. That is, a single isochrone is not expected to fit both components of the system because of their history of mass transfer. However, comparison with theoretical evolution tracks is still instructive. Thus, we considered the evolutionary models of Claret (1995, 1997) and Claret & Giménez (1995, 1998) (altogether referred to as the CG models). These models cover a wide range in both metallicity (Z) and initial helium abundance (Y), incorporate the most modern input physics, and use a value of 0.2\(H_p\) as the convective overshooting parameter. In our particular case, we adopted the metal abundance from the SED fit (see Table 7), which results in a value of \(Z = 0.005\). Using this metal abundance, the empirical chemical law of Ribas et al. (2000a) yields a helium abundance of \(n(\text{He})/n(\text{H}) = 0.084\), corresponding to \(Y = 0.25\). (The analysis of the disentangled spectrum of the primary in §4 provides a remarkable confirmation of this result.)

In Figure 9, we show the CG models for masses of 11.6 and 4.7\(M_\odot\), corresponding to the masses measured for the HV 5936 components. Despite its history of significant mass gain, the primary component has a luminosity in excellent agreement with theoretical expectations for a star of its mass and radius. This is not surprising, since it has been shown that the hydrodynamical relaxation time of the accretion process is short enough that the mass-gaining component in a nonconservative system is expected to behave like a normal star of its mass and radius (De Grève 1991, 1993). Empirical proof of this has been obtained from the study of Galactic Algol systems (García & Giménez 1990). The secondary, on the other hand, is significantly overluminous for its current mass. This is consistent with the behavior exhibited by the mass donors in Galactic Algol systems (Giuricin, Mardirossian, & Mezzetti 1983; Hilditch & Bell 1987).

The rotational velocity determined from the disentangled spectrum for the secondary is consistent with synchronization with the orbit (compare the values of \(v\sin i\) and \(v_{\text{sync}}\) in Table 7). This is expected, since the secondary completely fills its Roche lobe and tidal forces are very efficient at locking the star’s spin rate to follow the orbital motion. This agreement between observations and theoretical expectations provides a consistency check on the measurements of \(v\sin i\), stellar radius, and orbital properties. The primary component, however, is seen to have a rotational velocity that is ~25% larger than the synchronization value. The departure from unity is well beyond the observational uncertainties—but is not unprecedented or unexpected. The primaries of numerous Galactic Algol systems have been determined to rotate faster than their synchronous rate and even close to the centrifugal limit (see, e.g., van Hamme & Wilson 1990). A rotational velocity 25% larger than synchronization is well within the observed range. Angular momentum transfer through mass accretion is probably the most plausible model to explain the spin-up of Algol primaries (Huang 1966).

The factor of ~2 enhancement observed in the secondary’s surface He abundance, as discussed in §4, provides a strong constraint on the original masses of the stars in the HV 5936 system, particularly that of the secondary. The nature of this constraint is as follows: the initial mass of the current secondary must have been such that, by the time the star evolved to fill its Roche lobe (and commence mass transfer), the point in its interior where the He abundance was twice the surface value was at a radius that enclosed 4.7\(M_\odot\) of material (i.e., the current mass of the secondary). This interior point—now at the surface of the secondary—clearly must have been in the outer regions of its original H-burning core.
To exploit this constraint, we considered the evolution of four different simulated binary systems, constructed with the assumptions of (1) nonconservative mass exchange with 50% efficiency in the transfer of mass from the donor star to the mass-gaining star and (2) a fractional angular momentum loss proportional to the fractional mass lost to the system. The initial masses of these systems were 12 (current secondary) + 8 $M_\odot$ (current primary), 14 + 7 $M_\odot$, 16 + 6 $M_\odot$, and 18 + 5 $M_\odot$. The calculations were done following the formalism in Torres, Neuha¨user, & Wichmann (1998), but considering the nonconservative mass transfer expression in Vanbeveren et al. (1979). From these, we estimate initial orbital periods of 1.154, 1.318, 1.689, and 2.449 days and initial Roche lobe radii of 5.2, 6.1, 7.8, and 10.7 $R_\odot$, respectively, for the four mass combinations. The results showed that each of the systems experiences case A mass transfer (i.e., occurring during the core hydrogen-burning phase of the mass donor) and that all could eventually evolve to the configuration observed for HV 5936—but with different resultant surface He abundances for the mass donor. Using internal composition profiles computed by one of us (A. C.), we find that the surface He abundances of the initially 12, 14, 16, and 18 $M_\odot$ mass donors are enhanced by factors of 1.5, 2.6, 3.0, and 3.5, respectively, by the time the donor has been reduced to 4.7 $M_\odot$. The observed enhancement of ~2.0 is roughly midway between the 12 and 14 $M_\odot$ cases.

Taking into account all the results above, we postulate that the HV 5936 system began with initial masses of ~13 and ~7.5 $M_\odot$ for the current secondary and current primary, respectively. Case A mass exchange then resulted in the observed current masses of the components, the spinning up of the primary to a rotational rate faster than the synchronous rate, and the uncovering of processed material in the atmosphere of the secondary. The estimated initial mass of the secondary depends only weakly on our assumption of a 50% mass transfer efficiency (which is probably an upper limit). The primary’s initial mass is much more sensitive to this assumption, although it might be possible to constrain it further (and thus the transfer efficiency) by considering the spin-up process. Along with the He enhancement, the secondary’s surface should also exhibit a ~70-fold enhancement of $^{14}$N and a ~10-fold depletion of $^{12}$C and $^{18}$O, according to our interior composition models. These enhancements and depletions were assumed in the case II modeling of the secondary’s disentangled spectrum, as discussed in § 4. Because of the already low metallicity of this LMC star, the modifications in CNO abundances do not have a striking effect on the secondary’s spectrum. In Figure 7, we indicate the locations of the most prominent N ii lines. Even with their enhanced abundances, these lines are too weak to claim a positive detection, although they do appear to be features in the spectrum at their locations. Higher quality spectra will be required to confirm their presence and, thus, the surface enhancement of N.

6. The Interstellar Medium Toward HV 5936

Our analysis of HV 5936 provides some insight into the conditions of the interstellar medium (ISM) along the line of sight to the system. In this section we examine this information and also show how these data help constrain the relative position of HV 5936 within the LMC.

The column density of interstellar H i in the foreground of HV 5936 was measured by comparing the observed H i Lyα 1216.7 Å absorption-line profile (using the unbinned FOS data) with theoretical profiles consisting of a synthetic stellar spectrum convolved with an interstellar absorption profile. In general, the interstellar profile is constructed by assuming a component at 0 km s$^{-1}$ with $N$(H i) = $5.5 \times 10^{20}$ cm$^{-2}$, corresponding to Milky Way foreground gas (see, e.g., Schwering & Israel 1991), and a second component with an LMC-like velocity and a column density that is varied to produce the best fit to the data (as judged by visual inspection).

In examining the FOS data for HV 5936, we found no evidence for H i absorption at LMC velocities, and we found a Milky Way contribution at 0 km s$^{-1}$ of $5.0 \times 10^{20}$ cm$^{-2}$, slightly less than, but consistent with, the mean value of Schwering & Israel (1991). The best-fitting Lyα profile is shown in Figure 10, where we illustrate the unbinned FOS spectrum, the synthetic stellar spectrum (dotted curve), and the convolution of the synthetic spectrum with the interstellar profile (thick solid curve). Note that the bottom of the Lyα profile is filled in by geocoronal emission.

This notable absence of neutral LMC interstellar gas toward HV 5936 is consistent with the interstellar reddening results. The value of $E(B-V) = 0.047 \pm 0.004$ mag found for HV 5936 from the SED analysis is essentially identical to the mean value for 56 Milky Way foreground stars within 1° of the HV 5936 line of sight [$E(B-V) = 0.048$, from the data of Oestreicher, Gochermann, & Schmidt-Kaler 1995].

![Fig. 10.—Derivation of the interstellar H i column density toward HV 5936. The FOS data centered on the H i Lyα line at 1215.7 Å are shown (thin solid curve). Prominent stellar features (asterisks) and interstellar features are labeled. The dotted curve represents a synthetic spectrum of the HV 5936 system, constructed by combining two individual velocity-shifted spectra. The individual spectra were computed using Ivan Hubeny’s SYNSPEC spectral synthesis program with Kurucz ATLAS9 atmosphere models of the appropriate stellar parameters as inputs. The thick solid curve shows the synthetic spectrum convolved with an interstellar H i Lyα line computed with a Galactic foreground component of $N$(H i) = $5.0 \times 10^{20}$ cm$^{-2}$ at 0 km s$^{-1}$ (see § 4).]
Thus, there is no measurable contribution to \( E(B - V) \) from LMC material.

The lack of large amounts of LMC gas and dust toward HV 5936 provides an opportunity to examine some properties of the Milky Way ISM along a sight line passing completely through the Milky Way’s halo—but free of extragalactic contamination. In particular, the gas-to-dust ratio for this material is \( \mathcal{N}(\text{H i})/E(B - V) = 1 \times 10^{22} \text{ cm}^{-2} \text{ mag}^{-1} \), which is roughly twice the value found in the Galactic disk and suggests a “cleaner” ISM in the halo. In addition, the wavelength-dependent extinction curve derived from the SED analysis is now recognized to be a measure of the extinction properties of Galactic halo dust grains. This curve is shown in Figure 11, where the small symbols indicate the normalized ratio of model fluxes to observed fluxes while the thick solid curve shows the parameterized representation of the extinction curve, which was actually determined by the fitting process. The most remarkable feature of this curve is the very weak 2175 Å bump, which may be the weakest bump ever seen in Milky Way dust. The curve is consistent with the results of Kiszkurno-Koziej & Lequeux (1987), which show a weak trend of weakening bump strength and steepening 1500–1800 Å extinction with increasing height above the Galactic plane. The shape of the HV 5936 curve is very similar to those seen toward HV 982 and EROS 1044 (Papers II and III), whose total extinctions are dominated by Milky Way dust.

The ISM results for HV 5936 provide constraints on the position of the system within the LMC. Its apparent location places it within the outlines of LMC 4, the largest supergiant H II shell in the LMC (Goudis & Meaburn 1978; Meaburn 1980). The shell has a diameter of \( \sim 1.1 \) kpc, and HV 5936 is positioned northeast of the shell center and near the inside edge. A hint of the shell can be seen in Figure 1. The position of the shell coincides with a hole in the H I distribution (McGee & Milton 1966). The H I 21 cm emission-line data of Rohlls et al. (1984), obtained with a half-power beam width of 15′, reveal a total LMC H I column density of \( 2.4 \times 10^{20} \text{ cm}^{-2} \) at the position of HV 5936, with higher values to the east and comparable values in other directions. The minimum value of \( N(\text{H i}) \) seen in the general vicinity of HV 5936 is \( \sim 1.6 \times 10^{20} \text{ cm}^{-2} \), at a position 0′4 west of the system. While we have not established a rigorous upper limit for the nondetection of LMC H I Lyα absorption toward HV 5936, such a limit is certainly below \( 10^{20} \text{ cm}^{-2} \). Thus, while we cannot rule out the presence of localized, deep holes in the ISM distribution, the simplest explanation of both the HV 5936 gas and dust results is that the system lies at an undetermined distance above the main H I layer at its apparent location on the LMC.

7. THE DISTANCE TO HV 5936

The discussion in § 5 demonstrates that, despite the interesting evolutionary state of the HV 5936 system and the mass exchange that has occurred, the stellar properties appear well determined and well understood. In particular, the properties of the primary star are indistinguishable from those of a normal single star, which came by its mass through the normal star formation process. We can thus determine a distance to the system based on the results for the primary star, by combining its absolute radius \( R_P \) (derived from the classical EB analysis) with the distance attenuation factor \( (R_P/d)^3 \) (derived from the SED analysis). We find \( d_{\text{HV5936}} = 43.2 \pm 1.8 \) kpc, corresponding to a distance modulus of \( (V_0 - M_V)_{\text{HV5936}} = 18.18 \pm 0.09 \) mag.

The uncertainty in the distance is estimated from considering three independent sources of error: (1) the internal measurement errors in \( R_P \) and \( (R_P/d)^3 \), as given in Table 3; (2) uncertainty in the appropriate value of the extinction parameter \( R(V) \); and (3) uncertainty in the FOS flux scale zero point due to calibration errors and instrument stability. Straightforward propagation of errors shows that these three factors yield individual uncertainties of \( \pm 1.7 \), \( \pm 0.3 \) [assuming \( \sigma(R(V)) = \pm 0.3 \)], and \( \pm 0.4 \) kpc [assuming \( \sigma(FOS) = \pm 2.5\% \)], respectively. The overall 1 \( \sigma \) uncertainty quoted above is the quadratic sum of these three errors. It is dominated by the uncertainty in the primary’s radius, which alone accounts for 1.7 kpc in the error budget. Note that the only “adjustable” factor in the analysis is the extinction parameter \( R(V) \), for which we have assumed the value 3.1. Because of the very low reddening of the system, our distance result is very insensitive to this assumption. The weak dependence of the distance modulus on \( R(V) \) is given by \( (V_0 - M_V)_{\text{HV5936}} = 18.18 - 0.04|R(V) - 3.1| \).

We have considered the possibility that this distance result may be tainted because of the advanced evolutionary state of the secondary star. In general, the light-curve and radial velocity curve analyses are very insensitive to the properties of the EB’s components; i.e., the temperature ratio of the two stars, their mean radii, surface gravities, and relative contributions to the observed light in the optical spectral region are virtually model-independent and very well determined. These results tightly constrain the SED analysis, and so it would seem that the results could be compromised only if the secondary’s SED departs significantly from the shape predicted by an ATLAS9 model of the derived \( T_{\text{eff}}, \log g, [m/H] \), and \( v_{\text{micro}} \) values. The evidence, however, suggests that this is not the case. In support, we note the high quality of the fit to the combined SED of the system, which is comparable to our previous studies of systems containing wholly normal stars, and the consistency between the SED analysis and the independent modeling of...
TABLE 8  

| EB System       | References | \(d_{\text{EB}}\) (kpc) | \(d_{\text{MC}}\) (Case I)\(^a\) | \(d_{\text{MC}}\) (Case II)\(^b\) |
|-----------------|------------|-------------------------|-------------------------------|-------------------------------|
| HV 2274......... | 1, 2       | 47.0 ± 2.2              | 45.9                         | 47.0                          |
| HV 982........... | 2          | 50.2 ± 1.2              | 50.6                         | 50.7                          |
| EROS 1044....... | 3          | 47.5 ± 1.8              | 47.3                         | 47.4                          |
| HV 5936......... | 4          | 43.2 ± 1.8              | 44.0                         | 44.7                          |

\(^a\) Distance at a reference point at \((\alpha, \delta)_{1950.0} = (5^h24^m, -69^\circ47')\), corresponding to the center of the LMC’s bar, according to Isserstedt 1975. Adopted LMC orientation defined by an inclination angle of 38° and a line-of-nodes position angle of 168°, from Schmidt-Kaler & Gochermann 1992. This orientation is illustrated in Fig. 1.

\(^b\) Distance referred to the same reference point as case I. Adopted LMC orientation defined by an inclination angle of 34.7° and a line-of-nodes position angle of 122.5°, from van der Mare & Cioni 2001. In this case, the line of nodes runs approximately parallel to the long axis of the LMC’s bar.

References.—(1) Paper I; (2) Paper II; (3) Paper III; (4) this paper.

The disentangled optical spectra (see § 4). The only anomaly found is the probable modest enhancement of the secondary’s He abundance, which would have very small effect on the star’s SED. We have run a number of tests with the SED analysis, arbitrarily modifying the secondary’s SED (by varying \(T_{\text{eff}}, \log g, [m/H]\), or \(\ell_{\text{micro}}\)). Even relatively large changes have little effect on the derived system distance, because of the dominance of the primary in the combined SED. We thus conclude, based on both a lack of contrary evidence and the apparent robustness of the result, that uncertainties arising from the evolutionary state of the secondary are likely significantly smaller than the other sources of error noted above.

In Table 8, we show the individual system distances for HV 5936 and the other EBs in our study. We also list the implied distances to a standard reference point in the LMC, based on the assumption that the EBs are all located within a flat, disklke LMC whose spatial orientation is specified by an inclination angle and a position angle for the line of nodes in the plane of the sky. We choose the optical center of the LMC’s bar as the reference point and show two sets of LMC distances, based on two different assumptions about the LMC’s spatial orientation. Details are given in the notes to the table.

The results for HV 5936 in Table 8 clearly stand out from the others. This is partially explained by projection effects. Because HV 5936 lies relatively far from the adopted reference point and in the “near side” of the LMC, it is expected to be somewhat closer than the other systems. However, when the projection is taken into account, the distance implied for the LMC reference point is 44.3 ± 1.8 kpc, corresponding to a distance modulus of 18.23 ± 0.09 (from taking a simple mean of the two cases shown in Table 8). This is about 2 \(\sigma\) away from the mean of the other systems and suggests that the assumption that all the systems lie in the same flat disk may be invalid.

Although the relatively large uncertainty in the HV 5936 result prevents definitive conclusions, we suggest that HV 5936 lies “above” the extrapolated position of the LMC’s disk. This notion is consistent with, and actually suggested by, the interstellar results, which reveal no evidence for absorption by LMC H i and no measurable extinction by LMC dust along the HV 5936 sight line. This interpretation of the ISM data is complicated by the coincidence of HV 5936’s position in the sky with the supergiant shell LMC 4, toward which a very low H i 21 cm emission column density is observed. Depending on the patchiness of the H i, it is conceivable that a star located within or even behind LMC 4 could show an undetectably low H i absorption column density. This seems unlikely for HV 5936, however, since it is located near the eastern edge of LMC 4, where the 21 cm column density is \(\approx 2.10^{20}\) cm\(^{-2}\) and rises steeply toward the east. The simplest explanation is that HV 5936 just lies in front of most of the LMC’s interstellar matter. It is not clear why HV 5936 should occupy such a position, although this might well be related to the formation of shell LMC 4 itself. Likewise, it remains to be seen whether HV 5936 is a pathological object, in terms of its location, or is merely representative of a spatially extended stellar population in the northeast quadrant of the LMC.

Alternative explanations for the HV 5936 results include assuming a simple error in the spatial orientation of the LMC or perhaps a major structural feature, such as a warp, in the LMC’s disk. The latter may arise from strong past interactions between the Magellanic Clouds and the Milky Way. Both hypotheses would allow HV 5936 to lie close to the LMC’s disk (but still above it, given the ISM results), but require the disk to be closer to us than currently assumed. Unfortunately for these ideas, the required orientation for the LMC to necessitate an inclination angle (\(\sim 60^\circ\)) much steeper than previously measured. Moreover, structural studies of the LMC have revealed no evidence of a warp in the vicinity of HV 5936 (see, e.g., Olsen & Salyk 2002).

8. FINAL COMMENTS

The analysis presented here for HV 5936 has differed somewhat from those reported previously in Papers I, II, and III. Here our efforts have been focused more strongly on the physical properties of the stellar components and the evolutionary history of the binary system, rather than on the distance measurement. This arises from the interesting evolutionary state of this semidetached system and from its outlying location in the LMC. Because of its location, the implications of HV 5936’s individual distance for the distance to the LMC as a whole is not as firmly established as for our previously analyzed systems.

It is worth noting that HV 5936 is the first semidetached EB system to be used as a distance indicator for the LMC. Although our current analysis shows that semidetached binaries can be used successfully as such, there are a number of complications that call for the careful use of these systems. Among the related problems are (1) the lack of evolutionary cross checks, (2) the often very unequal component masses, effective temperatures, and luminosities that complicate the spectrophotometric analysis, (3) the large out-of-eclipse variations and distortions, and (4) the relative radii that are strongly dependent on the adopted mass ratio. Our success with HV 5936 springs directly from the high-quality observations available, in which the spectroscopic and photometric signatures of both stars are clearly present and separable.

Future distance studies within our program will be focused primarily on noninteracting systems lying closer to the apparent center of the LMC. We currently have
four detached systems under analysis, all of which can be expected to yield accurate distances and a number of cross checks to verify the results. In addition, two of these systems, EROS 1066 and MACHO 053648.7/C0691700 (see Fig. 1), have been specially selected to provide insight into the possible problem of line-of-sight extension of the LMC.

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