The Astronomical Journal, 126:902–905, 2003 August

THE DOUBLE SUPERGIANT BINARY OW GEMINORUM

Dirk Terrell,[1] D. H. Kaiser,[2] A. A. Henden,[3] R. Koff,[4] D. West,[5] S. Dvorak,[6]
A. Charles Pullen,[7] and Christopher P. Stephan[8]

Received 2003 February 25; accepted 2003 April 23

ABSTRACT

We present an analysis of recently published photometry of OW Geminorum during its 2002 eclipse season. The photometric data are analyzed simultaneously with previously published radial velocities. The results show that OW Gem consists of an F2 Ib–II primary with $M_1 = 5.8 \pm 0.2\ M_\odot$, $R_1 = 30.1 \pm 0.3\ R_\odot$ and a G8 IIb secondary with $M_2 = 3.9 \pm 0.1\ M_\odot$, $R_2 = 31.7 \pm 0.3\ R_\odot$. We discuss the evolutionary implications of these results.

Key words: binaries: eclipsing — binaries: spectroscopic — stars: individual (OW Geminorum) — supergiants

1. INTRODUCTION

OW Geminorum (HDE 258878) is a double supergiant binary consisting of an F2 Ib–II primary and a G8 IIb secondary with a rather large mass ratio, $q = m_2/m_1 = 0.67$, according to Griffin & Duquennoy (1993, hereafter GD93). GD93 discuss early indications that the system might be photometrically variable, but confirmation of the variability did not come until 1988 March when D.H. Kaiser, as part of a photographic nova patrol, discovered that it was fainter than normal. Kaiser, Baldwin, & Williams (1988) presented visual and photoelectric observations of the system in and around the minimum and correctly interpreted them as the 1.8 mag deep (V) eclipse of a binary with "exceptional characteristics." Kaiser (1988) searched 754 plates of the Harvard Photographic Plate Collection and found OW Gem faint on six of them. He presented an ephemeris with a period of 1258.56 days.

Williams (1989) continued to monitor OW Gem and found that the system was noticeably fainter on three nights near phase 0.23 by Kaiser's ephemeris. Williams carefully considered possible explanations for the decline in brightness but concluded that the only plausible explanation was that he had observed a secondary eclipse and that OW Gem had a highly eccentric orbit. This conclusion was further strengthened by Williams, Pray, & Wood (1991), who found no indication of a secondary eclipse at phase 0.5 in their photoelectric data. Williams & Kaiser (1991) presented visual observations of the 1991 primary eclipse and presented a slightly updated ephemeris. Because the period of OW Gem is very close to 3.5 yr, alternating eclipses occur near solar conjunction rendering them difficult to observe, as was the case for the 1991 eclipse.

GD93 presented reasonably well-sampled radial velocity curves for the two components and confirmed the large eccentricity, finding a value of 0.512 ± 0.011. The longitude of periastron, ω, was estimated to be $140\overset{\circ}{.}2 \pm 1\overset{\circ}{.}3$, which predicted that the secondary eclipse would last almost twice as long as the primary eclipse (~30 days vs. ~16 days) and would occur at phase 0.23, as observed by Williams. GD93 presented fits to the limited photometric data then available and found $M_1 = 5.9\ M_\odot$, $M_2 = 4.0\ M_\odot$, $R_1 = 30\ R_\odot$, and $R_2 = 35\ R_\odot$ and pointed out the "conundrum" of having two evolved and relatively high-mass stars with a large mass ratio in a binary. Recently, Kaiser et al. (2002) presented extensive photoelectric and CCD observations of the 1995 (BV) and 2002 eclipses ($UBVR_CI_C$). The 2002 primary eclipse minimum was particularly well placed for North American observers, and the observations show that the eclipse is partial (see Fig. 3 of Kaiser et al. 2002). In this paper, we present a simultaneous analysis of the GD93 radial velocities and the Kaiser et al. (2002) photometry and arrive at improved values for various parameters of the system.

2. ANALYSIS

We have performed a simultaneous analysis of the 2002 $UBVR_CI_C$ photometry and the GD93 radial velocities using a soon to be released version of the Wilson-Devinney (WD) program (Wilson & Devinney 1971; Wilson 1979, 1990) that includes Kurucz atmosphere models and bandpass-defined light curves as opposed to the effective wavelength scheme used in previous versions. In a simultaneous solution, the weights given to each set of observations must be carefully determined. The weights should reflect the scatter of the measurements, and the WD program gives output at each step from which the standard error, σ, can be calculated. It is sufficient to determine reasonably good starting values for the standard errors by examining plots of the observations and then adjust them as the solution progresses. Within a given light curve or radial velocity curve, WD can also apply relative weights. For all of the photometric observations in a given filter, we applied no relative weights. For the radial velocities, GD93 give reasons for weighting some more than

[1] Department of Space Studies, Southwest Research Institute, 1050 Walnut Street, Suite 400, Boulder, CO 80302; terrell@boulder.swri.edu.
[2] Crescent Moon Observatory, 2631 Washington Street, Columbus, IN 47201; dhkaiser@sprynet.com.
[3] Universities Space Research Association/US Naval Observatory, Flagstaff Station, P.O. Box 1149, Flagstaff, AZ 86002-1149; aah@nofs.navy.mil.
[4] Antelope Hills Observatory, 980 Anteleope Drive West, Bennett, CO 80102; bob.koff@tds.net.
[5] West Skies Observatory, P.O. Box 517, Derby, KS 67037; dwest61506@aol.com.
[6] Rolling Hills Observatory, 1643 Nightfall Drive, Clermont, FL 34711-2767; sdvorak@cfl.rr.com.
[7] Coyote Hill Observatory, 10215 Davis Road, Wilton, CA 95693; cpullen@pacsafe.com.
[8] Robert Clyde Observatory, 219 Andretti Drive, Sebring, FL 33876; stephanc@strato.net.

TABLE 1

Standard Errors Used for Data Analysis

Data Set	σ
U	0.0109[a]
B	0.0102
V	0.0156
R_C	0.0075
I_C	0.0093
RV_1	0.53 km s^{-1}
RV_2	1.92 km s^{-1}

[a] The units of the light curve standard errors are relative flux with the system light at maximum being approximately unity, thus the photometric errors are around 1%.

TABLE 2

Limb-Darkening Coefficients

Parameter	Derived Value	Theoretical Value[a]
$x_{1,U}$	0.92 ± 0.07	0.68 (0.05)
$x_{1,B}$	0.78 ± 0.04	0.74 (0.04)
$x_{1,V}$	0.51 ± 0.05	0.60 (0.06)
x_{1,R_C}	0.47 ± 0.05	0.50 (0.07)
x_{1,I_C}	0.51 ± 0.08	0.38 (0.07)
$x_{2,U}$	0.91 ± 0.28	1.01 (0.06)
$x_{2,B}$	0.90 ± 0.25	0.88 (0.01)
$x_{2,V}$	0.89 ± 0.28	0.72 (0.04)
x_{2,R_C}	0.71 ± 0.29	0.62 (0.06)
x_{2,I_C}	0.64 ± 0.28	0.54 (0.07)

[a] The quantity in parentheses is the "quality factor" from the Van Hamme tables and is analagous, but not strictly equal to, a standard deviation.

others, and we have applied their suggested values. Table 1 gives the standard errors we used for the various data sets.

The WD program uses the method of differential corrections assisted by the Levenberg-Marquardt algorithm (Marquardt 1963) to improve convergence. In many binaries this scheme, with a properly chosen λ, is sufficient to reliably iterate to a minimum in parameter space by adjusting all of the parameters at each iteration. For OW Gem, however, we found that the solution was highly unstable even when the parameter set was broken up into several subsets, no doubt a consequence of the rather large eccentricity's amplifying the effect of parameter correlations. In the end, we found that applying the method of multiple subsets (Wilson & Biermann 1976) in the most extreme form, with each subset containing only one adjusted parameter, greatly stabilized the solution, and we were able to reliably return to the same minimum from multiple starting points.

We fixed the primary's effective temperature at 7100 K based on the F2 Ib–II classification of GD93 and set the bolometric albedos and gravity darkening exponents at their theoretically expected values for convective envelopes. We used the linear limb-darkening law and adjusted the coefficients for each star. As expected, given the shallow depth of the secondary eclipse, the coefficients for the primary star were determined with significantly greater precision than those of the secondary. Table 2 shows the derived values and the expected values from the Van Hamme (1993) tables assuming a solar metallicity, $\log g_1 = 2.12$ and $\log g_2 = 2.03$. The error bars for the observed and theoretical values for the primary overlap, except for the U filter where the observed value is significantly larger than expected.

We used the ephemeris of Kaiser et al. (2002) to phase all of the observations. Figure 1 shows the fits to the phased

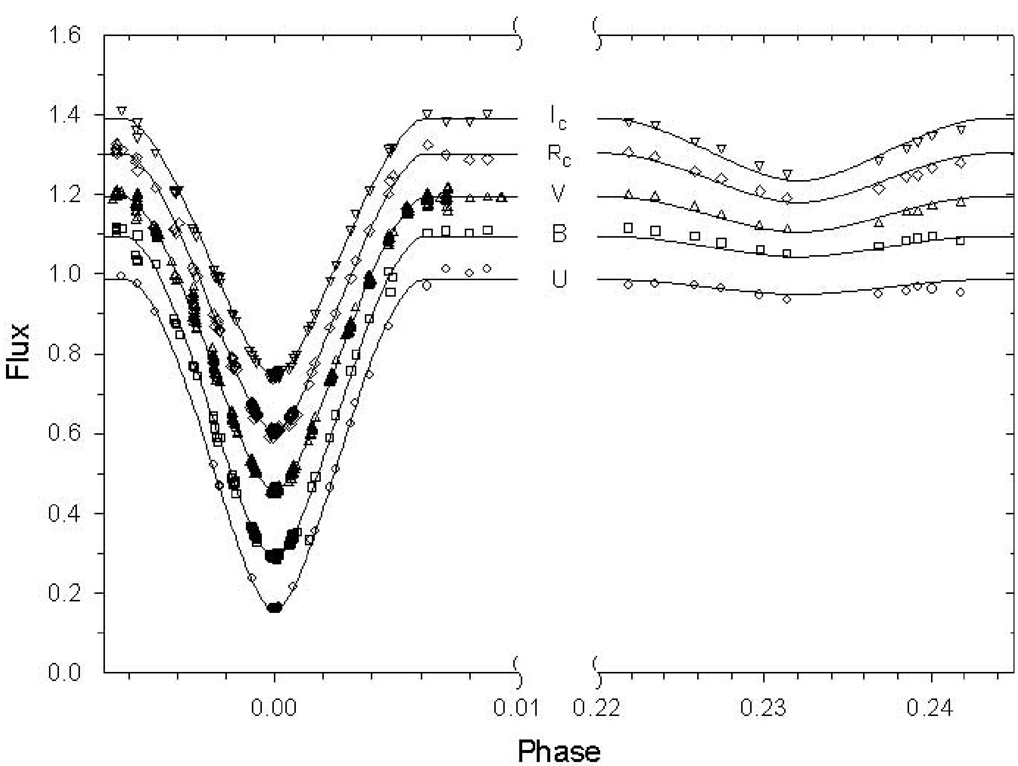

Fig. 1.—Photometric observations and computed fits for the 2002 eclipses of OW Gem. The light curves have been shifted vertically to separate them.

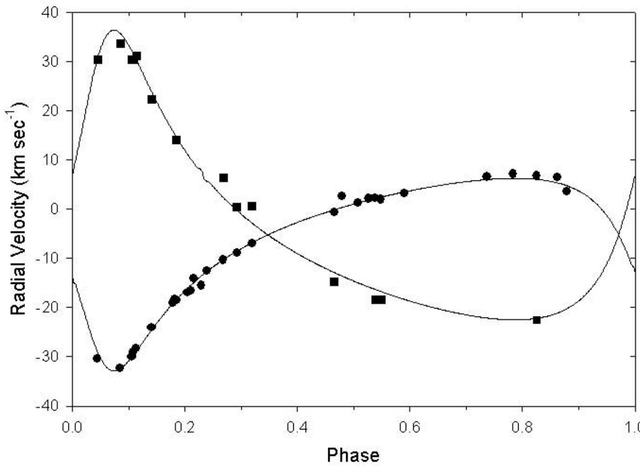

FIG. 2.—Radial velocities from GD93 and the computed fits

photometric data, and Figure 2 shows the fits to the phased velocity curves. Table 3 lists the derived parameters for the system. The derived spectroscopic parameters are in good agreement with those found by GD93, with the largest difference in the longitude of periastron where our value differs from theirs by a bit more than two standard deviations. The reader will note that parameters related to the geometry of the orbit, namely e and ω, are very precisely determined. This results from the fact that those parameters are very tightly constrained by the timing of the eclipses and their durations, both of which are well defined by the observations. The precision of our determination of the mass ratio is significantly higher than that of GD93 even though we use their radial velocities. This result is an excellent demonstration of the power of a simultaneous light-velocity analysis. Even though the light curves themselves have little, if any, information about the mass ratio in such a well-detached system, they do very strongly constrain the orbital geometry, and thus the mass ratio is limited to a smaller range of possible values. Van Hamme & Wilson (1984) and Wilson & Terrell (1998) discuss the merits of simultaneous solutions of multiple types of data.

TABLE 3
PARAMETERS OF OW GEMINORUM

Parameter	Value[a] (This Paper)	Value (GD93)
a ($R_\odot$)......................	1044.4 ± 8.8	...
e..............................	0.51718 ± 0.00002	0.515 ± 0.011
ω (deg).....................	143.08 ± 0 .02	140.2 ± 1.3
V_γ (km s^{-1}).............	−5.18 ± 0.14	−5.25 ± 0.16
i (deg)......................	89.08 ± 0.02	...
T_1 (K)	7100	7100
T_2 (K)	4917 ± 110	4800
Ω_1............................	35.15 ± 0.03	...
Ω_2............................	24.19 ± 0.01	...
q..............................	0.664 ± 0.002	0.67 ± 0.01
ϕ_0...........................	−0.1030 ± 0.0001	...
$L_1/(L_1+L_2)_U$.........	0.946 ± 0.008	...
$L_1/(L_1+L_2)_B$.........	0.924 ± 0.005	...
$L_1/(L_1+L_2)_V$.........	0.868 ± 0.006	...
$L_1/(L_1+L_2)_{R_C}$.......	0.815 ± 0.004	...
$L_1/(L_1+L_2)_{I_C}$........	0.761 ± 0.005	...
r_1 (side)	0.02961 ± 0.00002	...
r_2 (side)	0.03026 ± 0.00002	...
R_1 ($R_\odot$)....................	30.9 ± 0.3	30
R_2 ($R_\odot$)....................	31.7 ± 0.3	35
M_1 ($M_\odot$)..................	5.8 ± 0.2	5.9
M_2 ($M_\odot$..................	3.9 ± 0.1	4.0

[a] Quoted errors are 1 σ errors.

The results are in good agreement with the analysis of GD93. The mass and radius of the primary are found to be $5.8 \pm 0.2\ M_\odot$ and $30.9 \pm 0.3\ R_\odot$ respectively, and those of the secondary, $3.9 \pm 0.1\ M_\odot$ and $31.7 \pm 0.3\ R_\odot$. The derived surface gravities[9] of the two stars are $\log g_1 = 2.2$ and $\log g_2 = 2.0$. We find bolometric magnitudes of -3.6 and -2.0 for the primary and secondary giving luminosities of approximately 2100 and 500 $L_\odot$. These values are consistent with the luminosity classifications of Ib–II for the primary and II for the secondary as found by GD93.

We denote an intrinsic (i.e., unreddened) color by $(B-V)'$ and an observed color by $B-V$ with subscripts 1, 2, and C denoting the primary component, the secondary component, and the composite value for the binary, respectively. With an assumed intrinsic color for the primary, $(B-V)'_1$, and the magnitude differences between the two components in each filter, Δm_B and Δm_V, from the light-curve solution, we can compute the intrinsic composite color of the binary, $(B-V)'_C$, as

$$(B-V)'_C = (B-V)'_1 - 2.5 \log\left(\frac{1+10^{(-0.4\Delta m_B)}}{1+10^{(-0.4\Delta m_V)}}\right) .$$

Observations by A. A. H. of OW Gem at maximum light show that $V = 8.22$ and $(B-V)_C = 0.69$. According to the tables of Flower (1996), an F2 II star has $(B-V)' = 0.32$, and an F2 Ib star has $(B-V)' = 0.24$. If we take the intrinsic color for the primary to be the average of the two values from the Flower tables, we find that the value of $(B-V)'_C$ is 0.34. Clearly there is significant reddening along the line of sight to OW Gem, amounting to a color excess $E(B-V)_C = 0.35$. (We note that the nearby A0 star HD 46198 has Tycho magnitudes $B_T = 8.4$ and $V_T = 8.0$, so it also shows significant reddening.) It is customary to write the absorption in magnitudes in the V passband, A_V, as $A_V = R_V E(B-V)$, where R_V is the extinction constant and has a value of 3.2 in most regions of the sky. R_V could, in principle, be directly determined for OW Gem via the extinction curve method, since we have JHK magnitudes for the binary from the Two Micron All Sky Survey. Unfortunately, we do not have light curves in those passbands to determine the passband-specific luminosity ratios of the component stars and thus the expected composite colors in the infrared. We therefore take the usual value of $R_V = 3.2$ and find that the extinction in the V passband is 1.1 mag. The true distance modulus is, therefore, 10.9, yielding a distance of about 1500 pc. These values compare well with those of GD93, who estimated the distance modulus to be 11.1 and the distance 1600 pc.

3. EVOLUTIONARY STATUS

OW Gem presents quite a challenge when we try to uncover its evolutionary history. The basic dilemma is that

[9] CGS units.

the system consists of two stars of quite different masses that are in very short-lived stages of their evolution. If the two stars were formed together, both cannot possibly be in the red giant stage. The primary would have evolved to the red giant stage in about 7.5×10^7 yr, but the secondary would take over twice as long to reach that stage, by which time the primary would have evolved to a degenerate state.

One is then tempted to invoke the well-known solution to the Algol paradox: significant mass transfer from the once more massive secondary to the primary. However, as GD93 point out, this hypothesis is greatly weakened by several properties of OW Gem: the very small relative radii of the stars and the very large orbital eccentricity. At periastron, both stars are much smaller than their critical surfaces, and if the stars had somehow been much larger in the past, the tidal interactions should have circularized the orbit. We therefore agree with GD93 that large-scale mass transfer is not an appealing resolution to the OW Gem situation.

An interesting suggestion recently proposed by Eggleton (2002) is that OW Gem is a former triple system with the primary having formed from the merger of a close binary with parameters something like $4\ M_\odot + 2\ M_\odot$ and $P = 2$ days. Progenitor triple systems of the required characteristics are not uncommon and mergers should be common as well (Nelson & Eggleton 2001). The merger product might be expected to have rapid rotation, and although the primary star does appear to be rotating faster ($P_{\rm rot} = 163$ days $\pm$ 18 days) than the pseudosynchronous rate (about 500 days) according to GD93, it is not unusually rapid. Eggleton argues that the primary could have undergone a G/K supergiant stage just after the merger and had substantial angular momentum removed by stellar wind and magnetic braking during a period of enhanced activity. Eggleton and D. T. are currently planning detailed evolutionary models to test this hypothesis.

4. CONCLUSIONS

Our new data and analysis provide improved values for the parameters of OW Gem and confirm its position as a system of extreme importance in understanding binary star evolution. The system consists of two supergiants with masses of $M_1 = 5.8\ M_\odot$ and $M_2 = 3.9\ M_\odot$ and radii of $R_1 = 30.9\ R_\odot$ and $R_2 = 31.7\ R_\odot$. It does not seem possible to have a binary system evolve to the state in which OW Gem is currently observed, but if the primary star were once itself a binary, then various evolutionary scenarios are plausible. Detailed models will have to be constructed to test these hypotheses, and we hope that our results will provide a worthy test of their validity.

D. T. acknowledges the assistance of Keith Gleason at the University of Colorado Sommers-Bausch Observatory in allocating telescope time for this project.

REFERENCES

Eggleton, P. P. 2002, in ASP Conf. Ser. 279, Exotic Stars as Challenges to Evolution, ed. C. A. Tout & W. Van Hamme (San Francisco: ASP), 37
Flower, P. J. 1996, ApJ, 469, 355
Griffin, R. F., & Duquennoy, A. 1993, Observatory, 113, 53 (GD93)
Kaiser, D. H. 1988, Inf. Bull. Variable Stars, No. 3233
Kaiser, D. H., Baldwin, M. E., & Williams, D. B. 1988, Inf. Bull. Variable Stars, No. 3196
Kaiser, D. H., et al. 2002, Inf. Bull. Variable Stars, No. 5347
Marquardt, D. W. 1963, J. SIAM, 106, 2096
Nelson, C. A., & Eggleton, P. P. 2001, ApJ, 552, 664
Van Hamme, W. 1993, AJ, 106, 2096
Van Hamme, W., & Wilson, R. E. 1984, A&A, 141, 1
Williams, D. B. 1989, J. AAVSO, 18, 7
Williams, D. B., & Kaiser, D. H. 1991, J. AAVSO, 20, 231
Williams, D. B., Pray, D. P., & Wood, J. E. 1991, J. AAVSO, 20, 234
Wilson, R. E. 1979, ApJ, 234, 1054
———. 1990, ApJ, 356, 613
Wilson, R. E., & Biermann, P. 1976, A&A, 48, 349
Wilson, R. E., & Devinney, E. J. 1971, ApJ, 166, 605
Wilson, R. E., & Terrell, D. 1998, MNRAS, 296, 33