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ABSOLUTE PROPERTIES OF THE ECLIPSING TRIPLE STAR CO ANDROMEDAE: CONSTRAINTS ON CONVECTIVE CORE OVERSHOOTING

CLAUD H. SANDBERG LACY¹, GUILLERMO TORRES², ANTONIO CLARET³, DAVID CHARBONNEAU², FRANCIS T. O'DONOVAN⁴,
AND GEORGI MANDUSHEV⁵

¹ Physics Department, University of Arkansas, Fayetteville, AR 72701, USA; clacy@uark.edu

² Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; gtorres@cfa.harvard.edu, dcharbonneau@cfa.harvard.edu

³ Instituto de Astrofísica de Andalucía, CSIC, Apdo. 3004, E-18080 Granada, Spain; claret@iaa.es

⁴ NASA Postdoctoral Program Fellow, Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771, USA; ftod@caltech.edu

⁵ Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001, USA; gmand@lowell.edu

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ABSTRACT

Accurate absolute properties have been determined for the eclipsing triple star CO And (F8+F8) based on extensive differential photometry obtained by three robotic observatories and CfA spectroscopy. The eclipsing binary star orbit is circular with a period of 3.655 days. The triple nature of this system is revealed by more than a century of timings of minimum light, and by the presence of third light in the photometric orbits. The masses of the eclipsing pair are 1.289 ± 0.007 and 1.264 ± 0.007 solar masses, and the corresponding radii are 1.727 ± 0.021 and 1.694 ± 0.017 solar radii. These stars are synchronously rotating and are near the end of their main-sequence phase, at an age of about 3.6 Gyr. The much fainter widely separated third body appears to have a mass of about 0.8 solar masses. The distance to the system is 377 ± 25 pc.

Key words: binaries: eclipsing – binaries: spectroscopic – stars: fundamental parameters – stars: individual (CO And) – stars: rotation – stars: solar-type

Online-only material: machine-readable and VO tables

1. INTRODUCTION

The photometric variability of CO And (BD +46° 281, TYC 3268-398-1; $\alpha = 01^{\text{h}}11^{\text{m}}24^{\text{s}}.83$, $\delta = +46^{\circ}57'49''.3$, J2000.0; Sp F8+F8 V, $V = 10.70\text{--}11.22$) was announced by Geyer et al. (1955) from photographic measures, with the notation that it might be an eclipsing variable star. Shortly thereafter, Grigorewski (1956) measured times of four minima photographically and gave an eclipse ephemeris with a period of 11.0436 days. The Bamberg observers published their own times of eclipse (Reim 1957) and found a period of 1.827633 days. Dates of minima predicted on this basis were then measured photographically, visually, and with CCD detectors. Lacy guessed in 2002 December that the true period was probably twice this value since there was no sign of a secondary eclipse in his accurate differential photometry obtained with the URSA WebScope (Lacy 2003a), and later CfA spectroscopic work (below) has confirmed that the true orbital period is almost exactly twice the Reim (1957) value. In 2003, Charbonneau and collaborators began monitoring selected star fields looking for transits of exoplanets similar to those of HD 209458b. One of the fields that was measured serendipitously contained CO And. The positional coincidence was discovered in 2004 December, and we were able to extract very accurate photometry of the eclipsing binary star measured by the Sleuth telescope, part of the Trans-Atlantic Exoplanet Survey (O'Donovan et al. 2004). The combination of photometric and spectroscopic analyses of our accurate data enables the determination of precise absolute properties of the component stars and provides strong constraints on theories of stellar evolution.

2. OBSERVATIONS AND REDUCTIONS

2.1. Differential Photometric Observations

Our photometric work on CO And began in 2001 and is based on observations obtained with three robotic instruments: the

URSA WebScope at Kimpel Observatory (Lacy et al. 2001) on the campus of the University of Arkansas, the NFO WebScope at the NF/ Observatory (NFO; Grauer et al. 2008) near Silver City, NM, and the Sleuth telescope (O'Donovan et al. 2004) in California.

Kimpel Observatory (<http://ursa.uark.edu>) consists of a Meade 10 inch f/6.3 LX-200 telescope with a Santa Barbara Instruments Group ST8 CCD camera (binned 2×2 to produce 765×510 pixel images with 2.3 arcsec^2 pixels) inside a Technical Innovations Robo-Dome, and controlled automatically by an Apple Macintosh G4 computer. The observatory is located on top of Kimpel Hall on the Fayetteville campus of the University of Arkansas, with the control room directly beneath the observatory inside the building. Exposures of 60 or 120 s made through a Bessell V filter (2.0 mm of GG 495 and 3.0 mm of BG 39) were read out and downloaded by ImageGrabber (camera control software written by J. Sabby) to the control computer over a 30 s interval, then the next exposure was begun. The observing cadence was therefore about 90–150 s per observation. The variable star would sometimes be monitored continuously for 4–6 hr. CO And was observed by URSA on 104 nights during parts of nine observing seasons from 2001 December 2 to 2009 February 22. The total number of URSA observations is 5941. The frames were analyzed by a virtual measuring engine application written by Lacy that flat-fielded the images, automatically located the variable and comparison stars in the image, measured their brightnesses, subtracted the corresponding sky brightness, and corrected for the differences in airmass between the stars. Extinction coefficients were determined nightly from the comparison star measurements. They averaged $0.25 \text{ mag airmass}^{-1}$. CO And is TYC 3268-0398-1. The comparison stars were TYC 3268-0400-1 (comp; $V_T = 10.31$, $B_T - V_T = +1.24$) as listed in the *Tycho-2* Catalog; = Høg et al. 2000), and TYC 3268-0958-1 (ck; $V_T = 11.38$, $B_T - V_T = +1.44$). In measuring the URSA images, a square aperture with 30 arcsec sides was used. Both comparison stars are within 10 arcmin of the variable star (var).

Figure 1. Differential photometry for CO And obtained with the NFO, URSA, and Sleuth telescopes, along with our best-fit models. Residuals are shown at the bottom, with NFO and Sleuth displaced for clarity.

Table 1

Differential Photometric Observations of CO And in V Made with the URSA WebScope

Phase	V (mag)	HJD-2,400,000
0.48295	0.731	52245.58856
0.48320	0.739	52245.58948
0.48345	0.733	52245.59039
0.48370	0.739	52245.59132
0.48395	0.752	52245.59224

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

The comparison star magnitude differences (comp-ck) were constant at the level of 0.004 mag (standard deviation within a night), and 0.013 mag for the standard deviation of the nightly mean magnitude difference. The URSA differential magnitude (var-comp) of the variable star was referenced only to the magnitude of the comparison star, comp. The resulting 5941 URSA V magnitude differences (var-comp) are listed in Table 1 (without any nightly corrections) and plotted in Figures 1–3 (after the nightly corrections discussed below have been applied). The eclipse depths are 0.476 mag for the primary and 0.475 mag for the secondary. The precision of the raw variable star differential magnitudes is about 0.012 mag.

Another telescope we used is the NFO WebScope, a refurbished 24 inch Group 128 Cassegrain reflector with a 2k × 2k Kodak CCD camera, located near Silver City, NM. Observations consisted of 120 s exposures through a Bessell V filter. CO

Figure 2. Same as Figure 1, showing an enlarged view of the primary (deeper) eclipse.

Figure 3. Same as Figure 1, showing an enlarged view of the secondary (shallower) eclipse.

Table 2Differential Photometric Observations of CO And in *V* Made with the NFO WebScope

Phase	<i>V</i> (mag)	HJD-2,400,000
0.51444	1.100	53568.93531
0.51501	1.093	53568.93740
0.51558	1.083	53568.93949
0.51616	1.067	53568.94159
0.51673	1.057	53568.94368

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

And was observed by NFO on 143 nights during parts of five observing seasons from 2005 July 17 to 2009 February 15, yielding 5025 observations. Extinction coefficients were determined nightly from the comparison star measurements. They averaged 0.18 mag airmass⁻¹. The same comparison stars as those of the URSA telescope were used. In measuring the NFO images, a square aperture with 23 arcsec sides was used. The comparison star magnitude differences (comp–ck) were constant at the level of 0.007 mag (standard deviation within a night), and 0.010 mag for the standard deviation of the nightly mean magnitude difference. The differential magnitude (var–comps) of the variable star was referenced to the magnitude corresponding to the sum of the fluxes of the comparison star, comp, and the check star, ck. The resulting 5025 *V* magnitude differences (var–comps) are listed in Table 2 (without nightly corrections) and plotted in Figures 1–3 (including nightly corrections; see below). The precision of the variable star differential magnitudes is about 0.010 mag.

We noticed early on during the observations that the NFO magnitudes showed a small but significant offset from night to night, on the order of a hundredth of a magnitude. The origin of the offset is a variation in responsivity across the field of view of the NFO combined with imprecise centering from night to night. These variations are a well-known effect of the optics when using wide-field imaging telescopes such as the NFO. We have removed most of this variation by using dithered exposures of open clusters to measure this variation, fitting a two-dimensional polynomial (see Selman 2004), and subtracting the variation during initial reductions (photometric flat). The URSA observations, on the other hand, show this kind of effect to a much smaller extent. We have removed these nightly offsets before further analysis by using a procedure discussed in Section 3. The Sleuth photometry in Table 3 (9289 Sloan *r* magnitudes) was found to be free of these effects, though the raw data contained a number of clearly aberrant observations, which have been removed. A circular aperture of radius 30 arcsec was used in measuring differential magnitudes with Sleuth (O’Donovan et al. 2004).

2.2. Ephemeris

From the differential photometry of the three different telescopes, we have determined very accurate times of eclipse by using the method of Kwee & van Woerden (1956). We list these and other times of eclipse from the literature in Table 4. The minima now total 188. Uncertainties were taken from the literature, or were estimated for the older methods. We have adopted the usual convention that the deeper eclipse is the primary eclipse (type 1) and the other eclipse is the secondary eclipse (type 2). In the case of CO And, both eclipses are nearly the same depth,

Figure 4. Residuals from a linear eclipse ephemeris derived from recent very accurate CCD eclipse timings (years 2003–2009). The top panel shows results from the dates of primary eclipses, and the bottom panel from the dates of secondary eclipses. In both cases, the residuals are significantly positive prior to 1940, during the era of photographic eclipse timings. We believe that these positive residuals are a light travel time effect across an orbit with a third component in the system.

Table 3Differential Photometric Observations of CO And in Sloan *r* Made with the Sleuth Telescope

Phase	<i>r</i> (mag)	HJD-2,400,000
0.00006	0.479	52890.81791
0.00014	0.469	52934.68226
0.00020	0.473	52901.78444
0.00030	0.481	52923.71684
0.00042	0.479	52890.81925

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

but our differential photometry can distinguish them. The primary eclipse corresponds to the eclipse by the cooler star, which we refer to as A or c, of the hotter star, which we refer to as B or h. It turns out that A = c, the cooler star, is the more massive star (see below). We avoid referring to the stars as the primary or secondary component since this term is ambiguous in this system.

When we fitted a linear ephemeris to the dates of minimum light, we found that the modern, much more accurate CCD dates gave a different ephemeris than the older minima. We therefore used only the more recent (2003–2009) minima to determine an eclipse ephemeris to use in further analysis of our recently measured data:

$$\text{HJD Min I} = 2,453,764.44301(17) + 3.65533601(91),$$

where the uncertainties in the last digits are given in parentheses. The eclipse timing residuals based on this ephemeris are shown in Figure 4. The significantly positive mean residuals prior to year 1940 are likely due to the light travel time across an orbit with a third body. Thus, one should expect that third light might be present in the photometric analysis, which it is.

Table 4
Dates of Minimum Light for CO And

HJD −2,400,000	Eclipse Type	Uncertainty (days)	<i>O</i> − <i>C</i> (days)	Method	Reference
14672.48600	2	0.08000	0.03395	pg	1
15403.56200	2	0.08000	0.04275	pg	1
15677.85200	2	0.08000	0.18255	pg	1
16048.75300	1	0.08000	0.06694	pg	1
16781.63500	2	0.08000	0.05407	pg	1
16790.69000	1	0.08000	0.02927	pg	1
16845.53900	1	0.08000	0.01031	pg	1
17099.75700	2	0.08000	0.16184	pg	1
17185.59400	1	0.08000	0.09844	pg	1
17271.52900	2	0.08000	0.13305	pg	1
17525.61800	1	0.08000	0.17619	pg	1
17534.59300	2	0.08000	0.01285	pg	1
17797.80900	2	0.08000	0.04466	pg	1
17861.72400	1	0.08000	0.00872	pg	1
18680.60100	1	0.08000	0.07301	pg	1
18691.54200	1	0.08000	0.04801	pg	1
18857.81900	2	0.08000	0.00722	pg	1
18956.66800	2	0.08000	0.16215	pg	1
19053.46800	1	0.08000	0.09574	pg	1
20025.82000	1	0.08000	0.12836	pg	1
20548.53500	1	0.08000	0.13031	pg	1
20853.63300	2	0.08000	0.00776	pg	1
21467.81800	2	0.08000	0.09631	pg	1
21630.50000	1	0.08000	0.11585	pg	1
22244.70400	1	0.08000	0.22340	pg	1
22606.59900	1	0.08000	0.24014	pg	1
23651.77800	1	0.08000	0.00696	pg	1
23761.59000	1	0.08000	0.14496	pg	1
23803.54400	2	0.08000	0.06260	pg	1
24013.80200	1	0.08000	0.13878	pg	1
24055.74200	2	0.08000	0.04241	pg	1
24055.78400	2	0.08000	0.08441	pg	1
24055.82500	2	0.08000	0.12541	pg	1
24459.70400	1	0.08000	0.08978	pg	1
24788.74700	1	0.08000	0.15254	pg	1
24830.62400	2	0.08000	0.00682	pg	1
24830.66800	2	0.08000	0.03718	pg	1
24830.71200	2	0.08000	0.08118	pg	1
25148.74300	2	0.08000	0.09794	pg	1
25148.78700	2	0.08000	0.14194	pg	1
25236.51200	2	0.08000	0.13888	pg	1
25236.55900	2	0.08000	0.18588	pg	1
26217.83200	1	0.08000	0.00116	pg	1
26985.47300	1	0.08000	0.02160	pg	2
27003.70200	1	0.08000	0.02608	pg	1
27014.64700	1	0.08000	0.04709	pg	1
27042.22300	2	0.08000	0.11389	pg	2
27058.56200	1	0.08000	0.00388	pg	1
27060.36200	2	0.08000	0.02379	pg	2
27071.47000	2	0.08000	0.11820	pg	1
27367.48200	2	0.08000	0.04799	pg	2
27422.32100	2	0.08000	0.05695	pg	2
27453.47000	1	0.08000	0.13559	pg	1
28052.84200	1	0.08000	0.03248	pg	1
28067.49200	1	0.08000	0.06114	pg	2
28078.42200	1	0.08000	0.02513	pg	2
28396.53500	1	0.08000	0.12390	pg	2
28447.68400	1	0.08000	0.09820	pg	1
28950.28500	2	0.08000	0.09049	pg	2
29160.49800	1	0.08000	0.12167	pg	2
29193.36400	1	0.08000	0.08965	pg	2
29553.46300	2	0.08000	0.13805	pg	2
29573.45400	1	0.08000	0.02470	pg	2
29942.61700	1	0.08000	0.00123	pg	1
30337.51400	1	0.08000	0.11948	pg	1
31035.63100	1	0.08000	0.06730	pg	1
31079.49900	1	0.08000	0.07127	pg	1

Table 4
(Continued)

HJD −2,400,000	Eclipse Type	Uncertainty (days)	<i>O</i> − <i>C</i> (days)	Method	Reference
33868.51900	1	0.11000	0.06989	pg	3
33901.39800	1	0.11000	0.05087	pg	3
34652.54100	2	0.11000	0.02232	pg	3
34663.49400	2	0.11000	0.00931	pg	3
39088.29400	1	0.11000	0.02507	pg	4
39821.19300	2	0.02000	0.02920	vis	5
41599.50600	1	0.11000	0.02123	pg	4
42036.31000	2	0.11000	0.01258	pg	4
44485.39200	2	0.02000	0.01945	vis	6
44485.39300	2	0.02000	0.02045	vis	6
44823.48610	1	0.02000	0.00503	vis	7
44823.49500	1	0.02000	0.00387	vis	7
44823.51500	1	0.02000	0.02387	vis	7
44845.45000	1	0.02000	0.02685	vis	7
45205.48300	2	0.02000	0.00926	vis	7
45205.48950	2	0.02000	0.01576	vis	7
45205.49440	2	0.02000	0.02066	vis	7
45205.49640	2	0.02000	0.02266	vis	7
45205.49900	2	0.02000	0.02526	vis	7
45205.51100	2	0.02000	0.03726	vis	7
45269.45500	1	0.02000	0.01288	vis	8
45609.38470	1	0.02000	0.00367	vis	7
45609.39370	1	0.02000	0.00533	vis	7
46298.41300	2	0.02000	0.00621	vis	9
46331.31200	2	0.02000	0.00523	vis	9
46669.41890	1	0.02000	0.01691	vis	10
46669.42440	1	0.02000	0.01141	vis	10
46669.42900	1	0.02000	0.00681	vis	10
46700.51650	2	0.02000	0.01033	vis	11
46700.53800	2	0.02000	0.03183	vis	11
46744.40030	2	0.02000	0.03010	vis	11
46819.31700	1	0.02000	0.01241	vis	12
47029.47100	2	0.02000	0.01541	vis	13
47029.49300	2	0.02000	0.00659	vis	13
47029.51000	2	0.02000	0.02359	vis	13
47040.44000	2	0.02000	0.01242	vis	13
47804.41000	2	0.02000	0.00765	vis	14
48208.36800	1	0.02000	0.03573	vis	15
48482.47830	1	0.02000	0.00418	vis	16
48482.49000	1	0.02000	0.00752	vis	16
48504.42200	1	0.02000	0.00751	vis	16
48504.42800	1	0.02000	0.01351	vis	17
48504.43400	1	0.02000	0.01951	vis	16
48535.47800	2	0.02000	0.00685	vis	16
49639.40900	2	0.02000	0.01268	vis	18
49659.50300	1	0.02000	0.00233	vis	18
49661.33000	2	0.02000	0.00166	vis	18
49977.51400	1	0.02000	0.00090	vis	18
49997.62000	2	0.00100	0.00075	ccd	19
50317.45720	1	0.02000	0.00395	vis	20
50317.46700	1	0.02000	0.00585	vis	20
50317.47460	1	0.02000	0.01345	vis	20
50317.48080	1	0.02000	0.01965	vis	20
50436.26010	2	0.00100	0.00053	ccd	21
50688.48400	2	0.02000	0.00624	vis	20
51017.45220	2	0.02000	0.00580	vis	20
51017.45770	2	0.02000	0.00030	vis	20
51017.46190	2	0.02000	0.00390	vis	20
51017.46260	2	0.02000	0.00460	vis	20
51017.46750	2	0.02000	0.00950	vis	20
51017.46890	2	0.02000	0.01090	vis	20
51017.47160	2	0.02000	0.01360	vis	20
51017.47300	2	0.02000	0.01500	vis	20
51017.48000	2	0.02000	0.02200	vis	20
51465.24100	1	0.00100	0.00434	ccd	22
52245.65158	2	0.00016	0.00068	URSA	23
52267.58334	2	0.00011	0.00043	URSA	23

Table 4
(Continued)

HJD –2,400,000	Eclipse Type	Uncertainty (days)	<i>O</i> – <i>C</i> (days)	Method	Reference
52490.55720	2	0.00020	0.00121	ccd	24
52539.90630	1	0.00030	0.00085	ccd	25
52826.84740	2	0.00050	0.00192	URSA	26
52888.98908	2	0.00017	0.00096	Sle	27
52890.81667	1	0.00010	0.00103	Sle	27
52899.95568	2	0.00016	0.00036	Sle	27
52901.78355	1	0.00011	0.00016	Sle	27
52910.92212	2	0.00012	0.00007	Sle	27
52934.68220	1	0.00018	0.00046	URSA	26
52965.75230	2	0.00030	0.00021	URSA	26
52976.71844	2	0.00013	0.00034	Sle	27
52982.20090	1	0.00010	0.00020	ccd	28
53230.76320	1	0.00030	0.00075	URSA	29
53302.04200	2	0.00020	0.00100	ccd	30
53314.83760	1	0.00030	0.00092	URSA	31
53358.70090	1	0.00050	0.00019	URSA	31
53360.53090	2	0.00040	0.00252	URSA	31
53634.67810	2	0.00030	0.00048	URSA	31
53676.71610	1	0.00040	0.00115	URSA	31
53687.68078	1	0.00020	0.00017	NFO	31
53731.54510	1	0.00020	0.00011	URSA	32
53751.64940	2	0.00030	0.00007	URSA	32
54016.66120	1	0.00040	0.00001	URSA	32
54027.62700	1	0.00030	0.00020	NFO	32
54029.44880	2	0.00100	0.00607	ccd	33
54038.59240	1	0.00050	0.00081	URSA	32
54045.90390	1	0.00030	0.00002	NFO	32
54047.73100	2	0.00020	0.00055	NFO	32
54067.83650	1	0.00050	0.00060	NFO	32
54080.62810	2	0.00020	0.00147	NFO	32
54100.73420	1	0.00020	0.00028	NFO	32
54321.88200	2	0.00030	0.00025	URSA	34
54332.84740	2	0.00030	0.00036	NFO	34
54343.81310	2	0.00030	0.00067	URSA	34
54365.74560	2	0.00030	0.00018	URSA	34
54365.74560	2	0.00020	0.00018	NFO	34
54387.67850	2	0.00020	0.00070	NFO	34
54409.61030	2	0.00030	0.00048	URSA	34
54418.74740	1	0.00040	0.00076	NFO	34
54420.57600	2	0.00050	0.00018	URSA	34
54734.93520	2	0.00030	0.00048	NFO	34
54736.76080	1	0.00030	0.00159	URSA	34
54745.90020	2	0.00030	0.00053	NFO	34
54747.72900	1	0.00020	0.00060	NFO	34
54756.86680	2	0.00020	0.00006	NFO	34
54758.69570	1	0.00020	0.00130	NFO	34
54767.83230	2	0.00020	0.00044	NFO	34
54778.79870	2	0.00020	0.00005	NFO	34
54778.80030	2	0.00050	0.00155	URSA	34
54789.76460	2	0.00030	0.00016	NFO	34
54800.72950	2	0.00030	0.00127	NFO	34
54811.69620	2	0.00030	0.00058	NFO	34
54822.66220	2	0.00050	0.00058	URSA	34

Notes.

Method: pg = photographic; vis = visual; ccd = ccd camera; URSA = URSA WebScope (ccd, *V* filter); Sle = Sleuth telescope (ccd, *r* filter); NFO = NFO WebScope (ccd, *V* filter).

References. (1) Strohmeier & Bauernfeind 1968; (2) Reim 1957; (3) Grigorewski 1956; (4) Haeussler 1987; (5) Kreiner & Winiarski 1977; (6) Mikulasek 1980; (7) Mikulasek 1985; (8) Locher 1982; (9) Paschke 1988; (10) Mikulasek & Silhan 1988; (11) Mikulasek & Silhan 1990; (12) Peter 1987; (13) Mikulasek et al. 1992; (14) Peter 1990; (15) Peter 1991; (16) Mikulasek 1994; (17) Peter 1992; (18) Molik 2007; (19) Paschke 1996; (20) Mikulasek 1996; (21) Blaettler 1997; (22) A. Paschke 2007, private communication; (23) Lacy 2002; (24) Sarounova & Wolf 2005; (25) Dvorak 2003; (26) Lacy 2003b; (27) this paper; (28) Kotkova & Wolf 2006; (29) Lacy 2004; (30) Kim et al. 2006; (31) Lacy 2006; (32) Lacy 2007; (33) Hübscher & Walter 2007; (34) Lacy 2009.

2.3. Spectroscopic Observations and Orbital Solution

CO And was observed spectroscopically at the Harvard-Smithsonian Center for Astrophysics (CfA) from 2004 January until 2008 December, with an echelle spectrograph and a photon-counting Reticon detector on the 1.5 m Tillinghast reflector at the F. L. Whipple Observatory, on Mount Hopkins, Arizona. A total of 30 spectra were collected in a single echelle order 45 Å wide, centered at 5188.5 Å. The main features in this window are the lines of the Mg I b triplet. The resolving power of this setup is $\lambda/\Delta\lambda \sim 35,000$, and the signal-to-noise ratios of the spectra range from 17 to 32 per resolution element of 8.5 km s^{−1}.

Radial velocities were obtained with the two-dimensional cross-correlation algorithm TODCOR (Zucker & Mazeh 1994), which is designed to minimize line-blending effects. The template spectra, one for each component of the binary, were chosen from an extensive library of synthetic spectra based on model atmospheres by R. L. Kurucz (see Latham et al. 2002). The parameters of these templates are the effective temperature (T_{eff}), surface gravity ($\log g$), rotational velocity ($v \sin i$ when seen in projection), and metallicity ([M/H]). Following Torres et al. (2002), the optimum templates were selected by running extensive grids of cross-correlations with TODCOR exploring all possible parameter combinations, and seeking to maximize the average correlation value weighted by the strength of each exposure. Due to strong degeneracies among some of the template parameters, we initially set the surface gravity to $\log g = 4.0$ for both stars, and the metallicity to solar. The best-fitting templates have $T_{\text{eff}} = 6000$ K and $v \sin i = 25$ km s^{−1} for both components, and these were adopted for the velocity determinations. In Section 5, we describe further experiments to quantify the correlations mentioned above, and to fine-tune the temperature, $v \sin i$, and metallicity determinations using other information available for the system. These parameter refinements have no effect on the velocities presented here. Our spectroscopic determinations indicate the components are very similar in all their properties. The temperature difference is formally only 70 ± 50 K (the more massive star being marginally cooler), which is considerably smaller than the 250 K step in our template grid.

In addition to the velocities, we used TODCOR to obtain the light ratio between the components at the mean wavelength of our observations, following Zucker & Mazeh (1994). The result is $L_A/L_B = 1.012 \pm 0.025$ for the ratio between the marginally cooler and more massive component (star A), and the hotter but less massive star (B). Because the stars are so similar in temperature, the ratio should be very nearly the same at other wavelengths. We have nevertheless applied a small correction to the visual band based on synthetic spectra integrated over our spectral window and over the standard Johnson *V* bandpass, which resulted in $(L_A/L_B)_V = 1.016 \pm 0.025$. The same value holds for the Sloan *r* band.

As in previous work with similar spectroscopic material (see, e.g., Torres & Lacy 2009), we have used numerical simulations to assess the systematic errors in our velocities that may result from residual line blending in our narrow spectral window, or from shifts of the spectral lines in and out of this window as a function of orbital phase. Briefly, we generated synthetic composite spectra matching our observations by combining copies of the templates for each star, shifted to the appropriate velocities for each of the exposures as predicted by a preliminary orbital solution, and scaled to the observed light ratio. These synthetic observations were then processed with TODCOR in exactly the same way as the real spectra, and the resulting

Table 5
Radial Velocities of CO And in the Heliocentric Frame

HJD-2,400,000	RV _A (km s ⁻¹)	RV _B (km s ⁻¹)	(O-C) _A (km s ⁻¹)	(O-C) _B (km s ⁻¹)	Phase
53014.6383	-63.98	69.94	1.14	1.11	0.8740
53192.9600	-76.93	79.66	1.18	1.15	0.6580
53216.9240	90.82	-90.99	1.19	1.16	0.2139
53218.9106	-92.66	94.97	1.27	1.23	0.7574
53271.8907	95.68	-95.13	0.98	0.96	0.2513
53273.8639	-89.01	96.09	1.05	1.02	0.7911
53278.8487	81.97	-77.15	1.08	1.05	0.1548
53282.8293	93.97	-93.71	0.97	0.94	0.2438
53302.7013	-84.36	87.18	1.18	1.15	0.6802
53308.7154	85.25	-83.05	1.21	1.18	0.3255
53335.7696	-89.70	95.21	1.25	1.22	0.7268
53370.6105	97.32	-92.64	1.44	1.40	0.2583
53576.9852	-88.70	96.27	1.28	1.24	0.7168
53627.9296	-75.34	79.76	1.21	1.18	0.6538
53631.8237	-89.74	94.03	1.12	1.09	0.7191
53688.7390	90.24	-88.98	1.35	1.31	0.2896
53695.7241	90.01	-86.75	1.35	1.31	0.2006
53723.6081	-81.71	84.78	1.40	1.36	0.8289
53989.9589	-85.78	92.77	1.35	1.31	0.6952
54044.7068	-79.92	85.79	1.40	1.36	0.6727
54046.8378	95.58	-92.44	1.35	1.31	0.2557
54101.5809	94.81	-93.67	1.10	1.07	0.2319
54108.6195	80.32	-79.01	1.39	1.35	0.1575
54395.7966	-92.33	93.99	1.85	1.81	0.7213
54457.6753	-73.88	79.64	1.43	1.39	0.6496
54483.6124	-91.04	95.32	1.36	1.32	0.7453
54485.6593	88.31	-88.52	1.32	1.29	0.3053
54742.8690	-80.63	86.06	1.35	1.31	0.6709
54777.8005	91.91	-92.58	1.41	1.37	0.2272
54812.7287	-89.34	96.41	1.30	1.27	0.7826

Note. All corrections mentioned in the text are included.

velocities were compared with the input shifts. The differences for CO And are typically smaller than 1 km s⁻¹, and change systematically with phase as lines shift in and out of the 45 Å spectral window. Because of this, they have a non-negligible effect on the absolute dimensions of the binary, so they were applied to the raw velocities as corrections. The effect on the absolute masses is 0.8%, and the impact on the orbital semimajor axis used in computing the absolute radii is a smaller 0.25%. Similar corrections for systematics were applied to the light ratio based on the same simulations, and are already included in the value reported earlier.

The stability of the zero point of the CfA velocity system was monitored by means of exposures of the dusk and dawn sky, and small run-to-run corrections were applied in the manner described by Latham (1992). The final velocities, including these offsets as well as the corrections for systematics described previously, are listed in Table 5 along with their uncertainties. The median value for the velocity errors is 1.3 km s⁻¹ for both stars.

With these velocity measurements we carried out a weighted spectroscopic orbital solution for CO And, which is presented in Table 6 and shown graphically in Figure 5 along with the residuals. The ephemeris was held fixed at the results from Section 2, and the orbit was assumed to be circular since tests indicated that the eccentricity is not significant.

3. LIGHT CURVE MODELING

In order to remove the small nightly offsets in the differential photometry, we performed preliminary fits of the URSA and

Figure 5. Measured radial velocities and computed orbit for CO And. Filled symbols correspond to the more massive and marginally cooler star (star A), and the dotted line represents the center-of-mass velocity. Error bars are smaller than the symbol size. O-C residuals for both stars are shown at the bottom on an expanded scale.

Table 6
Spectroscopic Solution for CO And

Parameter	Value
Adjusted quantities	
P (days)	3.65533601 (fixed)
T_I (HJD) ^a	2,453,764.44301 (fixed)
K_A (km s ⁻¹)	93.40 ± 0.24
K_B (km s ⁻¹)	95.24 ± 0.24
γ (km s ⁻¹)	+1.66 ± 0.16
E	0 (fixed)
Derived quantities	
$M_A \sin^3 i$ (solar masses)	1.2837 ± 0.0072
$M_B \sin^3 i$ (solar masses)	1.2589 ± 0.0072
$Q = M_A/M_B$	1.0197 ± 0.0035
$a_A \sin i$ (10 ⁶ km)	4.695 ± 0.012
$a_B \sin i$ (10 ⁶ km)	4.787 ± 0.012
$a \sin i$ (solar radii)	13.630 ± 0.025
Other quantities pertaining to the fit	
N_A/N_B	30
Time span (days)	1798.1
σ_A (km s ⁻¹)	1.25
σ_B (km s ⁻¹)	1.22

Note. ^a This epoch corresponds to the eclipse of the less massive and marginally hotter star by the more massive one, which is the deeper minimum.

NFO light curves by using the Nelson–Davis–Etelzel model (Popper & Etzel 1981; Etzel 1981) as implemented in the EBOP code. The nightly residuals, which were typically less than 0.01 mag and were uncorrelated with phase, were removed from each light curve. A few anomalous NFO values were also removed at this stage. These corrections improved the residual standard deviations of the URSA data by about 19%, and those from NFO by a more significant 45%.

The corrected differential photometry for CO And from the NFO, URSA, and Sleuth telescopes was analyzed with the same Nelson–Davis–Etelzel light-curve model used above, as implemented in the JKTEBOP code of Southworth et al. (2007). This model is adequate for well-detached systems such as this with small relative radii (which are approximately 0.12 for both stars in CO And). The adjustable parameters are the cooler/hotter central surface brightness ratio (J_c), the orbital inclination angle (i), the sum of the relative radii in units of the semimajor axis ($r_h + r_c$), the radius ratio ($k = r_c/r_h$), a phase shift, and the magnitude at quadrature. Experiments solving also for the eccentricity (e) and longitude of periastron (ω) did not yield statistically significant values of e , consistent with indications from spectroscopy, so this quantity was set to zero for the remainder of the analysis. Limb darkening was accounted for by adopting a linear law, consistent with our experience that more complicated laws do not improve the accuracy of the fits significantly with the amount and precision of the data at hand.

We have again checked on this assumption by doing numerical experiments fitting the NFO light curve data with a variety of nonlinear limb-darkening laws, including quadratic (Claret 2000; Claret & Hauschildt 2003; Diaz-Cordoves et al. 1995), logarithmic (Claret 2000; Claret & Hauschildt 2003; van Hamme 1993), and square root (Claret 2000; Claret & Hauschildt 2003; Diaz-Cordoves et al. 1995; van Hamme 1993),

using the observed values of temperature and log g to determine the coefficients. Our results are that the fitted values of radii are 0.2% smaller when using the nonlinear coefficients, and the inclination is smaller by 0.05 degrees. The adopted errors in the radii in Table 9 are more than five times larger than these errors, so we choose to use the simpler linear limb-darkening law with these data.

The linear limb-darkening coefficient x was constrained to be the same for both stars, given their very similar properties. The gravity brightening coefficient y was set to 0.34 for both stars as determined from their temperature and surface gravity, and the calculations by Claret (1998). The mass ratio was held fixed at the spectroscopic value of $q = M_A/M_B = 1.0197$. Third light (L_3) was also considered, and was found to be statistically significant for all three telescopes. We discuss this further below.

Initial solutions indicated a difficulty common in partially eclipsing systems with similar components, which is that while the sum of the radii is well constrained by the photometry, the radius ratio k is not. Solutions with rather different values of k deliver equally satisfactory fits to the data. As shown, e.g., by Popper (1984, 1987), Andersen et al. (1980, 1991), and others, an accurate external constraint such as that provided by the spectroscopic light ratio can serve to break the degeneracy. We have used this technique here.

Grids of JKTEBOP solutions were run for all three data sets over a range of fixed values of k between 0.98 and 1.06. For each k we determined the photometric light ratio (L_c/L_h) along with all other elements, and then used the resulting relation between k and L_c/L_h to apply the spectroscopic constraint, $L_A/L_B = (L_c/L_h)_V = (L_c/L_h)_r = 1.016 \pm 0.025$, and determine the radius ratio. Other elements were interpolated to the same value of k . The procedure is illustrated for NFO in Figure 6, with the URSA and Sleuth relations being similar. We propagated the uncertainty in L_c/L_h to k and the rest of the photometric elements, as shown by the shaded areas in the figure. The results are summarized in Table 7 for the three telescopes.

We considered three sources of uncertainty in the light-curve elements, which are also listed in the table. One (ε_1) is the error that comes directly from the spectroscopic constraint, propagated through to all interpolated variables. Another is a statistical component (ε_2) due to the observational (photometric) uncertainties. We calculated it for each parameter using the option in JKTEBOP to perform Monte Carlo simulations, which provides a more realistic assessment than the formal errors otherwise returned by the program. We carried out 500 of these simulations, each time generating independent synthetic data sets assuming Gaussian error distributions. For the third contribution to the errors (ε_3) we considered the interagreement between the solutions for the three telescopes (or only NFO and URSA for the wavelength-dependent parameters), and adopted half of the total range as a conservative uncertainty.

The adopted values of the light-curve elements are the weighted average of the three determinations in Table 7 (except for the passband-specific quantities J_c , L_3 , and $x_h = x_c$), where the weights were computed as usual from the inverse square of the uncertainties, given by $\varepsilon = \text{sqrt}(\varepsilon_1^2 + \varepsilon_2^2)$. The final uncertainties were obtained by combining in quadrature the error of the weighted average with ε_3 . These final results and uncertainties are given in Table 8.

As indicated earlier, the third light parameter from our fits is significant for all three telescopes, ranging from 1.4% (URSA) to 7.7% (Sleuth). At face value these suggest contamination of the light curve by another star. However, because of the large

Table 7
Light-curve Solutions for CO And, Following the Application of the Spectroscopic Constraint on the Light Ratio

Element	NFO (V)			URSA (V)			Sleuth (Sloan <i>r</i>)			ε_3
	Param	ε_1	ε_2	Param	ε_1	ε_2	Param	ε_1	ε_2	
k	1.025	0.013		1.014	0.013		1.019	0.013		
$r_h + r_c$	0.24963	0.00055	0.00056	0.24810	0.00047	0.00090	0.25306	0.00050	0.00065	0.0027
r_h	0.12325	0.00053	0.00028	0.12319	0.00101	0.00045	0.12533	0.00055	0.00032	0.0011
r_c	0.12638	0.00107	0.00028	0.12491	0.00053	0.00045	0.12773	0.00106	0.00033	0.0014
i	87.001	0.035	0.036	86.953	0.021	0.059	86.808	0.033	0.055	0.096
J_c	0.96629	0.00090	0.00050	0.98815	0.00027	0.00082	0.97823	0.00075	0.00081	0.011 (V)
L_3^a	0.0369	0.0076	0.0071	0.0140	0.0061	0.0107	0.0769	0.0071	0.0091	0.011 (V)
$x_h = x_c$	0.649	0.035	0.034	0.475	0.032	0.059	0.711	0.032	0.039	0.087 (V)
N	5012			5941			9289			
Time span (days)	1308.7			2639.0			55.9			
σ (mmag)	5.265	0.024		9.4638	0.0038		5.1508	0.0072		

Note. ^a $L_c/L_h = 1.016 \pm 0.025$ and $L_c + L_h + L_3 = 1$ for each solution.

Table 8

Adopted Photometric Elements and Uncertainties for CO And

Element	Value and Error
k	1.0193, 0.0093
$r_h + r_c$	0.2505, 0.0025
r_h	0.1241, 0.0012
r_c	0.1265, 0.0015
i (deg)	86.94, 0.10
J_c (V)	0.979, 0.011
J_c (r)	0.9782, 0.0011 ^a
L_3 (V)	0.023, 0.016 ^b
L_3 (r)	0.062, 0.020 ^b
$x_h = x_c$ (V)	0.588, 0.095
$x_h = x_c$ (r)	0.711, 0.050 ^a

Notes.

^a Internal errors only.

^b Corrected for contamination from field stars (see the text). In both bands (V and r), $L_c/L_h = 1.016 \pm 0.025$. L_3 is defined in this model such that $L_h + L_c + L_3 = 1$.

photometric apertures we used, and the object's relatively low galactic latitude of -15.8 deg, the chance of contamination from background sources is not negligible and must be considered before interpreting the L_3 values. The Sleuth aperture is the largest ($30''$ radius), and within it there are no fewer than 10 faint stars listed in the USNO-B1.0 catalog (Monet et al. 2003). Of these, the seven closest are within the URSA aperture, and only the four closest affect NFO. Adding up the light contribution of these stars we determined corrections to the measured L_3 values, which are very small for NFO (0.0024) and URSA (0.0078), and more significant for Sleuth (0.0154). Errors in these values were estimated through Monte Carlo simulations, assuming a 0.4 mag uncertainty for the photographic magnitudes of these faint sources. The corrected values of L_3 for the V and r passbands are listed in Table 8.

The stars in CO And are essentially spherical, and both eclipses are partial, with 76.9% of the light of Star B being lost at the primary eclipse, and 74.9% of the light of star A blocked at the secondary eclipse.

The limb-darkening coefficients (x) determined in our solutions are not far from the theoretical values based on model atmospheres. Our estimate for the V band, 0.588 ± 0.095 , is intermediate between the values of 0.697 and 0.556 found in the tabulations by Claret (2000) and van Hamme (1993), respectively. Our determination for the Sloan *r* band, 0.711 ± 0.050 ,

Table 9

Absolute Dimension of CO And

Parameter	Cooler Star (A)	Hotter Star (B)
Mass (solar masses)	1.2892, 0.0073	1.2643, 0.0073
Radius (solar radii)	1.727, 0.021	1.694, 0.017
Log g (cgs)	4.074, 0.011	4.0822, 0.0089
$v \sin i$ (km s ⁻¹)	24.1, 1.5	23.8, 1.5
$v \sin i$ (sync) (km s ⁻¹)	23.9, 0.3	23.4, 0.2
T_{eff} (K)	6140, 130	6170, 130
Log L/L_{sun}	0.580, 0.038	0.572, 0.038
BC(V) (mag) ^a	-0.03, 0.10	-0.02, 0.10
M_{bol} (mag)	3.281, 0.096	3.303, 0.094
M_V (mag)	3.31, 0.15	3.33, 0.15
$E(B-V)$ (mag)	0.09, 0.03	
Distance (pc)	377, 25	
a (solar radii)	13.650, 0.025	
[m/H]	+0.01, 0.15	

Notes.

^a Bolometric corrections from Flower (1996). The error includes contributions from the temperature uncertainties as well as an additional 0.10 mag we have added in quadrature, to be conservative. We have adopted $T_{\text{eff}}(\text{Sun}) = 5780$ K and $M_{\text{bol}}(\text{Sun}) = 4.732$, to be consistent with the zero point of the bolometric corrections.

is slightly larger than the value 0.639 given by Claret (2000), but perhaps still consistent given that our error estimate for this passband is strictly internal. For more extensive comparisons between theory and observation, the reader is referred to the work by Claret (2008).

4. ABSOLUTE DIMENSIONS

The combination of the spectroscopic and light-curve elements yields the absolute properties of CO And, which are summarized in Table 9. The relative errors in the masses are about 0.6%, and in the radii 1.2% or better, which are among the best obtained for eclipsing binaries. Based on the discussion in Sections 2.3 and 3, we believe these errors to be realistic, and to therefore represent the true accuracy of the measurements (not merely the formal precision).

Effective temperatures are more difficult to determine accurately. While the light curves typically constrain the temperature ratio very well, the absolute scale is considerably more uncertain. The strong correlation between temperature and metallicity in our narrow spectral window prevents us from determining T_{eff} (and [m/H]) directly from our spectra. However, with an

Figure 6. Grid of photometric solutions with JKTEBOP for the NFO data of CO And, for a range of fixed values of $k = r_c/r_h$. Each panel shows the variation of one of the light-curve elements as a function of k , and the top left panel illustrates the application of the spectroscopic constraint on the light ratio ($L_A/L_B = L_c/L_h = 1.016 \pm 0.025$) to derive the final value of k . Values and corresponding uncertainties for all other elements interpolated to this value of k are shown by the dashed line and shaded area, and are listed in Table 7. Similar grids were run for the URSA and Sleuth data.

independent estimate of the temperature such as from photometry, it is possible to resolve the degeneracy and determine both quantities. We follow this procedure here.

To better quantify the spectroscopic $T_{\text{eff}}/[m/H]$ correlation, we reran the grids of cross-correlations in Section 2.3 for a range of metallicities between $[m/H] = -1.0$ and $+0.5$, in steps of 0.5 dex. We did this for two values of the surface gravity bracketing the final values in Table 9 ($\log g = 4.0$ and 4.5), and then interpolated to the exact gravity for each star. Because the photometric temperatures described below correspond to the combined light, we combined the individual spectroscopic temperatures by weighting by the fractional luminosity of each star. In this way, we constructed a table of mean spectroscopic temperature as a function of metallicity. With an estimate of the mean temperature described below, the metallicity may then be read off.

External information on temperature can be obtained from color indices based on standard photometry for the combined light of CO And, together with color/temperature calibrations. Brightness measurements for the binary are available in a variety of photometric systems and are collected in Table 10, along with color indices for which reliable calibrations exist. The Two Micron All Sky Survey (2MASS) and Carlsberg Meridian Catalog measurements were taken out of eclipse, and we assume

that the *Tycho-2* and two-armed spiral shock (TASS) values are relatively unaffected by the eclipses given the large number of measurements. We adopt the weighted average of the three independent measurements in the Johnson *V* band. The eight indices listed in Table 10 are not independent, but are still useful to give a sense of the scatter in the temperature results. For the color/temperature conversion we use three different calibrations by Ramírez & Meléndez (2005), Casagrande et al. (2006), and González-Hernández & Bonifacio (2009), all of which include correction terms for metallicity.

The chemical composition needed for those corrections is unknown to begin with, although it represents only a second-order effect in the photometric T_{eff} . Reddening is potentially a much more important effect. We have estimated the reddening for CO And in two different ways. One is based on the Strömgren indices of Hilditch & Hill (1975) listed in Table 10, and a table of standard indices such as that of Perry & Johnston (1982). The result is $E(B - V) = 0.116$. Another estimate may be obtained from dust maps such as those of Schlegel et al. (1998), which give a total reddening along the line of sight to the binary of $E(B - V)_{\text{tot}} = 0.119$. The maps of Burstein & Heiles (1982) give a nearly identical estimate of 0.118, which is probably coincidental. We adopt the average of the two, $E(B - V)_{\text{tot}} = 0.118$. The fraction of this latter value that applies

Table 10
Standard Photometry for CO And (Combined Light)

Passband/Color Index	Value and Error	Reference
B_T	11.345, 0.070	1
V_T	10.829, 0.068	1
J	9.474, 0.023	2
H	9.302, 0.018	2
K_s	9.185, 0.019	2
V	10.705, 0.090	3
I_C	9.972, 0.088	3
V	10.740, 0.026	4 ^a
V	10.65, 0.03	5 ^b
$u-b$	1.493, 0.02	5 ^b
$v-b$	0.555, 0.02	5 ^b
$b-y$	0.391, 0.02	5 ^b
B_T-V_T	0.516, 0.098	
$V-J$	1.228, 0.039	
$V-H$	1.400, 0.036	
$V-K_s$	1.517, 0.036	
$J-K_s$	0.289, 0.030	
V_T-K_s	1.644, 0.071	
$V-I_C$	0.730, 0.093	

Notes.

^a Average of three determinations taken out of eclipse.

^b Single measurement, so error is assigned conservatively.

References. (1) *Tycho-2* (Høg et al. 2000); (2) 2MASS (Cutri et al. 2003); (3) TASS (Droege et al. 2006); (4) Carlsberg Meridian Catalog (1999–2006); (5) Hilditch & Hill 1975.

to CO And depends on the distance to the system, which is also an unknown quantity initially. The distance is a function of the known radii, the unknown temperatures, the apparent V magnitude, bolometric corrections (which we take from Flower 1996 as a function of temperature), and the extinction $A(V) = 3.1 \times E(B - V)$. Once an estimate of the distance is obtained, we then take the average of the dust-map and Strömgren reddening values.

Most of the quantities mentioned above depend on one another in complicated ways, but it is possible to iterate this procedure to solve for the reddening, the distance, the individual temperatures, and the metallicity. Reddening-corrected temperature estimates from the eight color indices and three different calibrations typically agree within 150 K. As indicated earlier, the light-curve fits provide strong information on the temperature ratio (or difference), and we use the central surface brightness ratio J_c in the visual band along with Popper (1980) Table 1 to estimate ΔT_{eff} . The procedure converges quickly, and leads to a consistent set of parameters that are listed in Table 9. The uncertainty in the individual temperatures, metallicity, and distance are dominated by the error in the reddening. Separate estimates of the distance for each component are in excellent accord (to within 1 pc), another sign of internal consistency. The temperature difference between the components is very small (30 ± 20 K), and agrees with the rough value from spectroscopy but has less uncertainty. The final values of temperature are $T_A = 6140 \pm 130$ K and $T_B = 6170 \pm 130$ K, and the reddening is $E_{B-V} = 0.09 \pm 0.03$.

The small amount of third light in our photometric measurements suggests the presence of another star in the system. It is possible that this is the same object responsible for the long-term trends in the eclipse timing residuals we reported in Section 2. The velocity residuals from our spectroscopic orbit show no evidence of a trend, but this is not surprising given the short

interval of our observations (less than 5 yr) compared to the timescale of the timing variations (at least 100 yr; see Figure 4). We also examined our spectra using an extension of TODCOR to three dimensions (Zucker et al. 1995), but we see no sign of a third star. This is also not unexpected given that L_3 implies a 4 mag difference relative to the binary, in the visual band.

5. COMPARISON WITH STELLAR MODELS

Our accurate determination of the absolute properties of CO And, including the estimated value of metallicity, which is not typically known for eclipsing binaries, allows for a stringent test of recent stellar evolution models. We begin by using the calculations from the Yonsei–Yale series (Yi et al. 2001), with an updated convective core overshooting prescription described by Demarque et al. (2004). The masses of the components are large enough that a small convective core is beginning to develop in their centers, and overshooting has a measurable effect.

Using the interpolating routines provided by the modelers, we computed evolutionary tracks for the exact masses we measured. These are shown in the top panel of Figure 7 in a diagram of $\log g$ versus T_{eff} . There is a small uncertainty in the location of these tracks that comes from the observational errors in the masses; we represent this by the shaded areas in the figure. The chemical composition of the models was adjusted to provide the best match with the observations, and indicates $Z = 0.0148$, corresponding to $[\text{Fe}/\text{H}] = -0.09$. This is in good agreement with the measured metallicity of $[\text{m}/\text{H}] = +0.01 \pm 0.15$. The age determined from the models is 3.65 Gyr, based on this diagram. The corresponding isochrone is shown with the dashed line. We note that while the errors in the absolute temperatures are relatively large compared to the separation between the tracks (130 K), the temperature difference from photometry is much better determined, and is indicated in the figure ($\sigma[\Delta T_{\text{eff}}]$). Both our photometric estimate and our spectroscopic estimate indicate the components are nearly indistinguishable in temperature, the more massive star being marginally cooler. The models also indicate a very small difference, although an accurate estimate is made difficult by limitations in the interpolating scheme that lead to a jagged appearance of the isochrones. This is seen in the lower panels of Figure 7, which nevertheless illustrate the good overall fit to the individual radii and effective temperatures as a function of the best-measured property, the mass.

The stars in CO And are seen to be very near the end of their main-sequence phase, just prior to leftward turn (“blue hook”) that precedes the stage of their evolution across the Hertzsprung gap in which they burn hydrogen in a shell. It is precisely at their present phase that the consequences of overshooting are seen more clearly and are better tested, since it has the effect of extending the hydrogen-burning main sequence toward lower temperatures in this diagram. The implementation of overshooting in the Yonsei–Yale models, parameterized in terms of a simple multiplicative scale factor α_{ov} to the local pressure scale height, is such that α_{ov} ramps up gradually from zero (when there is no convective core at all) up to a maximum of $\alpha_{\text{ov}} = 0.2$ as the mass of the model increases. At the metallicity and mass of CO And, the α_{ov} in the interpolated tracks is approximately 0.08–0.09, or about half of the maximum value. The location of the binary in Figure 7 is consistent with this value. If α_{ov} were much smaller than this, the theoretical main sequence would retract toward hotter temperatures, leaving the stars in an unphysical position in the diagram.

Figure 7. Top: observations of CO And compared against evolutionary tracks from the Yonsei-Yale series (Yi et al. 2001; Demarque et al. 2004), calculated for the exact masses we measure (solid lines). The shaded areas represent the uncertainty in the location of the tracks that comes from the mass uncertainties. The best-fitting age and metallicity are 3.60 Gyr and $Z = 0.0148$ (corresponding to $[\text{Fe}/\text{H}] = -0.09$ in these models). The corresponding isochrone is shown by the dashed line. Also indicated is the observational uncertainty ($\sigma_{\Delta T_{\text{eff}}}$) in the temperature difference between the components, which is much smaller than the errors in the absolute temperatures. Middle: radius as a function of mass, along with isochrones for the best-fit metallicity between 3.2 Gyr and 4.0 Gyr in steps of 0.2 Gyr. The thick line corresponds to the best-fit age, and error bars are indicated by the shaded regions. Bottom: the same as above, for effective temperature vs. mass.

We examined also the match between the CO And properties and the stellar evolution models of the Victoria-Regina group (VandenBerg et al. 2006), which use a different prescription for overshooting based on a parameterized version of the Roxburgh criterion (Roxburgh 1978, 1989). The comparison with the corresponding isochrones is illustrated in Figure 8. We find a very good concordance for a metallicity of $[\text{Fe}/\text{H}] = -0.11$, once again consistent with our spectroscopic estimate, and an age of 3.40 Gyr. The lower panels of the figure show the

Figure 8. Observations of CO And compared against model isochrones from the Victoria-Regina series (VandenBerg et al. 2006). Top: isochrones for the best-fit metallicity of $[\text{Fe}/\text{H}] = -0.11$ and ages from 3.0 Gyr (left) to 3.8 Gyr (right), in steps of 0.2 Gyr. The best matching age of 3.40 Gyr is indicated with the thick line. Middle: radius as a function of mass. Bottom: temperature as a function of mass.

comparison with the radii and temperatures. The models indicate a temperature difference of 41 K (the more massive star being cooler), in excellent agreement with our estimate of 30 ± 20 K.

In order to explore the impact of convective core overshooting more quantitatively, we have made use of the Granada models by Claret (2004), which use the same prescription as the Yonsei-Yale models and allow greater flexibility in adjusting the overshooting parameter. The metallicity that best matches the observations for these models is $Z = 0.016$, corresponding to $[\text{Fe}/\text{H}] = -0.03$. Once again this is consistent with the spectroscopically measured composition. In Figure 9, we show the evolutionary tracks for a range of values of α_{ov} , including calculations with no overshooting at all (top panel). The observations are clearly inconsistent with $\alpha_{\text{ov}} = 0.00$, and from the lower panels it appears that the minimum value that is able to match

Figure 9. Comparison of the observations for CO And against stellar evolution models by Claret (2004), for the best-fit composition of $Z = 0.016$ (corresponding to $[\text{Fe}/\text{H}] = -0.03$). The different panels show the effect of changing the overshooting parameter α_{ov} . The best-fit age from the models with $\alpha_{\text{ov}} = 0.10$ is 3.8 Gyr, and for $\alpha_{\text{ov}} = 0.20$ is 3.9 Gyr.

the observations is around $\alpha_{\text{ov}} = 0.10$, or slightly higher. This is not very different than the value used in the Yonsei–Yale models, although it is also clear by comparison with the top panel in Figure 7 that there are differences in the tracks from these two models even for similar amounts of overshooting. These differences have to do mostly with the details of the physics in each set of calculations. For example, the Yonsei–Yale models include helium diffusion, while the Granada models do not. There are

also differences in the equation of state, in the radiative opacities, and in the numerical methods. In any case, we conclude that the observations point to a lower limit for α_{ov} of about 0.10 for the Granada models, and perhaps somewhat smaller for the Yonsei–Yale models, and that they clearly exclude zero overshooting. The age of the system implied by the Granada models for $\alpha_{\text{ov}} = 0.10$ is 3.8 Gyr, and for $\alpha_{\text{ov}} = 0.20$ it is 3.9 Gyr. These are both slightly older than derived from the other models.

Additional stellar properties provided by the stellar evolution models include the absolute magnitudes in various passbands. These may be compared with the measured brightness of CO And, and used as a check on the distance reported earlier. For this test, we selected the best-fit Yonsei–Yale isochrone discussed above. After converting the near-infrared 2MASS magnitudes in Table 10 to the ESO system of the isochrone with the transformations of Carpenter (2001), and correcting all measures for interstellar extinction, the average distance for the V , I_C , J , H , and K passbands is 370 pc, very close to our previous estimate.

Finally, the stellar evolution models also allow us to make a rough estimate of the mass of the third star in CO And implied by the L_3 parameters in the light-curve fits. Using the same best-fit Yonsei–Yale isochrone from above, we find that the measured V -band and r -band third light parameters are consistent with being produced by a star of approximately 0.8 solar masses, or slightly larger. If this object is physically associated with the binary and is responsible for the light-travel time effect seen in Figure 4, the semimajor axis of its orbit around CO And would correspond to an angular separation of 0.09 arcsec if the period is 100 yr, or 0.25 arcsec if $P = 500$ yr. Confirmation should be possible with high-resolution imaging techniques.

6. CONCLUDING REMARKS

As a result of our intensive spectroscopic and photometric monitoring, the absolute masses of CO And are now determined to 0.6% accuracy and the radii to 1.2%, and these are among the best available for any eclipsing binary. In addition, we have established the effective temperatures, as well as estimating the overall metallicity. The latter quantity has not been determined for many eclipsing binaries, and is important because it reduces the degrees of freedom in the comparison with theory. Unfortunately, the precision of $[\text{Fe}/\text{H}]$ (and T_{eff} to some extent) is limited in this case by poor knowledge of interstellar extinction in the direction of the star. This could perhaps be remedied with additional and more accurate absolute photometric observations. Nevertheless, the combination of M , R , T_{eff} , and $[\text{Fe}/\text{H}]$ provides unusually strong constraints on stellar evolution theory. Comparison with current models yields an excellent fit to the observations, and indicates the stars are near the end of their main-sequence phase, at an age of about 3.6 Gyr. Because of their position near the blue hook at the end of the main sequence, we are able to put constraints on the degree of core overshooting, which is clearly non-zero in this case.

With masses around 1.3 solar masses, CO And is an important addition to well-studied main-sequence systems in the mass interval (approximately 1.1–1.7 solar masses) where convective overshooting is ramped up in evolutionary models. Only GX Gem and BW Aqr are listed by Torres & Lacy (2009) to be in a similar evolutionary state, both of them more massive than CO And.

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