ABSOLUTE PROPERTIES OF THE ECLIPSING BINARY SYSTEM AQ SERPENTIS: A STRINGENT TEST OF CONVECTIVE CORE OVERSHOOTING IN STELLAR EVOLUTION MODELS

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ABSTRACT

We report differential photometric observations and radial-velocity measurements of the detached, 1.69 day period, double-lined eclipsing binary AQ Ser. Accurate masses and radii for the components are determined to better than 1.8% and 1.1%, respectively, and are \( M_1 = 1.417 \pm 0.021 \, M_\odot \), \( M_2 = 1.346 \pm 0.024 \, M_\odot \), \( R_1 = 2.451 \pm 0.027 \, R_\odot \), and \( R_2 = 2.281 \pm 0.014 \, R_\odot \). The temperatures are 6340 \( \pm \) 100 K (spectral type F6) and 6430 \( \pm \) 100 K (F5), respectively. Both stars are considerably evolved, such that predictions from stellar evolution theory are particularly sensitive to the degree of extra mixing above the convective core (overshoot). The component masses are different enough to exclude a location in the H-R diagram past the point of central hydrogen exhaustion, which implies the need for extra mixing. Moreover, we find that current main-sequence models are unable to match the observed properties at a single age even when allowing the unknown metallicity, mixing length parameter, and convective overshooting parameter to vary freely and independently for the two components. The age of the more massive star appears systematically younger. AQ Ser and other similarly evolved eclipsing binaries showing the same discrepancy highlight an outstanding and largely overlooked problem with the description of overshooting in current stellar theory.

Key words: binaries: eclipsing – stars: evolution – stars: fundamental parameters

Online-only material: machine-readable tables and VO tables

1. INTRODUCTION

The eclipsing binary AQ Ser (GSC 00340−00588, BD+03 3015, \( V = 10.58 \)) was discovered as a variable star by Hoffmeister (1935). Its correct period of 1.6874 days and eclipse ephemeris were determined much later by Soloviev (1951). The light curve shows relatively deep (0.6 mag) and nearly identical primary and secondary eclipses, and the spectral types of the stars have been reported as F5 and A2 (Hill et al. 1975), although the latter classification for the less massive star is probably too early. The system has been little studied since its discovery, other than the occasional measurement of times of eclipse.

The main motivation for this work is to present new photometric and spectroscopic observations of AQ Ser, with which we determine the first time accurate absolute dimensions of the system and establish the evolutionary status of the stars. Both components appear to be at the very end of their hydrogen-burning phase, a location of the H-R diagram in which only a few other well-measured eclipsing binaries are found. The predicted properties of such stars from stellar evolution theory are especially sensitive to the degree of convective core overshooting adopted in the models, and a previous study by Clausen et al. (2010) has highlighted the difficulties that current models appear to have in reproducing the stellar properties of both components at a single age. The newly determined absolute dimensions for AQ Ser allow us an opportunity to revisit this problem here.

2. OBSERVATIONS AND REDUCTIONS

2.1. Differential Photometry

Photometric measurements of AQ Ser were determined by two different and independent robotic observatories: the Undergraduate Research Studies in Astronomy (URSA) WebScope, and the Neely and Farley Observatory (NFO) WebScope. The URSA WebScope uses a 10 inch Meade LX200 Schmidt–Cassegrain telescope with an SBIG ST8 CCD camera, housed in a Technical Innovations RoboDome on the roof of the Kimpel Hall on the University of Arkansas campus at Fayetteville, and is controlled by an Apple Macintosh G4 computer in a nearby control room. The field of view is about 20\( \times \)30 arcminutes. Observations with a Bessel \( V \) filter were carried out from 2003 June to 2011 July, producing a total of 8642 science frames from 80 s exposures. The two comparison stars for AQ Ser (“var”), both within 8 arcminutes of the variable star, were GSC 00340−00252 (“comp”; \( V = 10.99, G5 \, v \)) and GSC 00341−00211 (“ck”; \( V = 11.60, G2 \, v \)). It was eventually found that the ck star is a low-amplitude variable with a sinusoidal variation of half-amplitude 0.017 mag and a period of about 4 yr. Differential magnitudes in this study were therefore based on the var−comp magnitudes only.

The NFO WebScope is located near Silver City (New Mexico) in a roll-off roof structure, and consists of a 24 inch Cassegrain reflector with a field-widening correcting lens near the focus (see Grauer et al. 2008). At the focus is a camera based on the Kodak KAF-4301E CCD chip, with a field of view of about 27\( \times \)27 arcminutes. AQ Ser was observed at the NFO between 2005 January and 2007 June, producing a total of 6694 observations from 80 s exposures with a Bessel \( V \) filter.

All images were measured using a computer application (Measure) that matched a pattern file with the image, and then determined the differential magnitude after correction for dark current, sky brightness, and responsivity variations across the field of view.

As we have noted in the past (e.g., Lacy et al. 2008), the telescopes we used in this study produce systematic shifts of a few hundredths of a magnitude in the photometric zero point from night to night, and in the case of the NFO WebScope, from
one side of the German equatorial mount axis to the other. The shifts are very much less for the URSA WebScope than for the NFO, which shows that this is an effect of the optical system being used, and is not intrinsic to the stars themselves. The offsets are due to a non-uniform responsivity across the field of view, combined with imprecise centering from night to night. In the case of the NFO, we removed most of this effect by using dithered exposures of open clusters to fit a two-dimensional (2D) polynomial function to the responsivity variations, resulting in a photometric flat that is included in the initial data reduction procedures. Residual offsets remaining after this process were then removed by using an initial photometric orbital fit model (see Section 4) to determine the values of the nightly offsets and to remove them from the data. In this case, 130 nightly shifts were removed from the URSA data, and 197 shifts were removed from the NFO data. The typical precision of the final AQ Ser data sets is about 9 mmag for URSA and 5 mmag for NFO. The measurements including nightly corrections are listed in Table 1 (URSA) and Table 2 (NFO).

### 2.2. Spectroscopy

Spectroscopic observations of AQ Ser were carried out at the Harvard-Smithsonian Center for Astrophysics using an echelle spectograph on the 1.5 m Tillinghast reflector at the F. L. Whipple Observatory (Mount Hopkins, Arizona). A single echelle order 45 Å wide was recorded with an intensified photon-counting Reticon detector, at a central wavelength near 5190 Å that includes the Mg i b triplet. The resolving power of these observations is $\lambda/\Delta\lambda \approx 35,000$. We gathered 39 spectra between 2004 March and 2008 June, with signal-to-noise ratios ranging between 22 and 41 per resolution element of 8.5 km s$^{-1}$.

All our spectra appear double-lined. Radial velocities were obtained using the 2D cross-correlation technique TODCOR (Zucker & Mazeh 1994), with templates chosen from a large library of calculated spectra based on model atmospheres by R. L. Kurucz (see Nordström et al. 1994; Latham et al. 2002). The four main parameters of the templates are the effective temperature $T_{\text{eff}}$, rotational velocity ($v \sin i$ when seen in projection), metallicity [m/H], and surface gravity log $g$. The ones affecting the velocities the most are $T_{\text{eff}}$ and $v \sin i$. Consequently, we held $g$ fixed at values of 4.0 for both stars, which is near the final values reported below in Section 5, and we assumed solar metallicity. The optimum $T_{\text{eff}}$ and $v \sin i$ values were determined by running grids of cross-correlations, seeking the maximum of the correlation coefficient averaged over all exposures and weighted by the strength of each spectrum (see Torres et al. 2002). The rotational velocities we obtained are $v \sin i = 59 \pm 10$ km s$^{-1}$ for the hotter and less massive star (hereafter star A) and $v \sin i = 73 \pm 10$ km s$^{-1}$ for the cooler one (star B). The significant rotational line broadening in both stars and the relatively low signal-to-noise ratios cause the uncertainties above to be fairly large, and also prevent us from establishing the temperatures accurately. Only a rough estimate of $T_{\text{eff}}$ could be obtained. The values adopted from our analysis in Section 5 are $T_{\text{eff}} = 6430$ K for the less massive component and $T_{\text{eff}} = 6340$ K for the other. The uncertainty in these values has little effect on the velocities.

We also determined the light ratio at the mean wavelength of our observations (which is close to the $V$ band), following the prescription by Zucker & Mazeh (1994). We obtained $\ell_B/\ell_A = 1.05 \pm 0.04$, formally indicating that the cooler and more massive star of the system is visually the brightest.

As in previous studies using similar spectroscopic material, we made an assessment of potential systematic errors in our radial velocities that may result from residual line blending as well as lines shifting in and out of our narrow spectral window as a function of orbital phase (see Latham et al. 1996). We did this by performing numerical simulations analogous to those described by Torres et al. (1997), and we applied corrections to the raw velocities based on these simulations to mitigate the effect. The corrections were typically less than 2.5 km s$^{-1}$ for the hotter star and less than 2 km s$^{-1}$ for the cooler star, which are smaller than our internal velocity errors ($\sim 5$ km s$^{-1}$). The effect of these corrections on the absolute masses is minimal.

Finally, the stability of the zero point of our velocity system was monitored by taking nightly exposures of the dusk and dawn sky, and small run-to-run corrections (typically under 1 km s$^{-1}$) were applied to the velocities as described by Latham (1992). The adopted heliocentric velocities including all corrections are listed in Table 3, together with their uncertainties and the residuals from our adopted orbital solution described below.

### 3. Ephemeris

A total of 48 times of eclipse for AQ Ser were gathered from the literature, and were obtained by photographic, visual, photoelectric, or CCD techniques. From the 27 photoelectric/

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### Table 1

Differential V-band Measurements of AQ Ser from the URSA WebScope

| HJD (2,400,000+) | Orbital Phase | $\Delta V$ (mag) |
|-----------------|--------------|-----------------|
| 52814.60641     | 0.0963       | −0.366          |
| 52814.60833     | 0.0975       | −0.396          |
| 52814.61022     | 0.0986       | −0.365          |
| 52814.61212     | 0.0997       | −0.366          |
| 52814.61399     | 0.1008       | −0.375          |

**Note.** Orbital phase is computed with the ephemeris in Section 3.

(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.)

### Table 2

Differential V-band Measurements of AQ Ser from the NFO WebScope

| HJD (2,400,000+) | Orbital Phase | $\Delta V$ (mag) |
|-----------------|--------------|-----------------|
| 53377.03321     | 0.4000       | −0.390          |
| 53377.03484     | 0.4010       | −0.390          |
| 53377.03647     | 0.4019       | −0.390          |
| 53377.03806     | 0.4029       | −0.390          |
| 53377.03970     | 0.4038       | −0.386          |

**Note.** Orbital phase is computed with the ephemeris in Section 3.

(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.)
Table 3

| Parameter | Value |
|-----------|-------|
| $P$ (days) | 1.6874305 |
| $M_{\text{eff}}$ (HD-2,400,000) | 53.399.92270 |
| $K_B$ (km s$^{-1}$) | +20.58 ± 0.58 |
| $e$ | 127.27 ± 0.80 |
| $e$ | 120.8 ± 1.0 |
| $e$ | 0.0 (fixed) |
| Derived quantities | |
| $M_A \sin^3 i (M_\odot)$ | 1.300 ± 0.023 |
| $M_B \sin^3 i (M_\odot)$ | 1.369 ± 0.021 |
| $q = M_B / M_A$ | 1.054 ± 0.011 |
| $a_B \sin i (10^6 \text{ km})$ | 2.953 ± 0.018 |
| $a_B \sin i (10^6 \text{ km})$ | 2.803 ± 0.023 |
| $\sigma_B (\text{km s}^{-1})$ | 8.274 ± 0.043 |

Other quantities pertaining to the fit

$N_{\text{obs}}$ | 39 |

Time span (days) | 1559.9 |

Notes.

*a* Ephemeris adopted from Section 3.

*b* Based on the physical constants $GM_\odot$ and $R_\odot$ adopted by Torres et al. (2010).

Figure 1. Top: measured radial velocities for AQ Ser along with our best-fit orbit model. Solid circles correspond to the photometric primary (hotter and less massive star), and open circles to the secondary. The horizontal dotted line represents the center-of-mass velocity. Phase 0.0 corresponds to the eclipse of the hotter component. Bottom: $O-C$ residuals from the best orbital fit (same symbols as above).

CCD measurements we determined a preliminary ephemeris, and detected no significant trends indicative of any period changes in the $O-C$ residuals. A large number of additional timing measurements (167 in total) were derived from our own URSA and NFO differential photometry described previously. Of these, 39 timings are based on eclipse events with reasonably good coverage, i.e., with observations on both the ascending and descending branches of the primary or secondary minima. These were measured using either the traditional Kwee & van Woerden (1956) method (KvW) or a parabolic fit, or with an alternate technique relying on fitting a synthetic light-curve model to the observations, with the model being computed using the Wilson–Devinney (W-D) code (Wilson & Devinney 1971) and subsequent improvements by Vaz et al. (2007) pertaining to the ephemeris determination. For the latter method we had all light-curve parameters fixed to values close to our final solutions reported later, and adjusted only the time of eclipse. The results from these three procedures were then weight-averaged (see below). We considered measurements from URSA and NFO separately. For the 128 URSA/NFO eclipses with only partial coverage, many with observations on only one of the branches, we first predicted the approximate center of the event using the preliminary ephemeris above, and then adjusted this value using the W-D modeling just described.

Realistic uncertainties for these eclipse timings are not easy to establish, and can depend not only on the quality of the...
measurements, but also in our case on the method used to determine them. We proceeded as follows. We initially considered the uncertainties from our own measurements to be equal to the internal errors from each method, and solved for a linear ephemeris adjusting (scaling) these uncertainties by iterations so as to achieve reduced \( \chi^2 \) values near unity. This was done separately by method (KvW, parabolic, or W-D fits), telescope (URSA, NFO), and binary component (primary, secondary), with 12 groups in all. Similarly, for the measurements from the literature we considered the photographic and visual timings together as a group, and the CCD and photoelectric timings as another, separately for the primary and secondary. For the final fit, minima measured from our URSA or NFO data by more than one method were merged together into weighted averages with corresponding uncertainties. All 215 timings (124 for the primary eclipse, 91 for the secondary) are reported in Table 5 along with their final, rescaled errors. The resulting linear ephemeris (HJD) is

\[
\text{Min I} = 2,453,399.982270(47) + 1.68743059(17)E, \quad (1)
\]

with the figures in parentheses representing uncertainties in units of the last significant digit. Residuals from the above fit are listed in Table 5, and show no obvious pattern as a function of time. Using only the secondary timings we find a mean phase for the secondary eclipse of 0.50010 \( \pm \) 0.00008. This is consistent with 0.5, supporting our assumption of a circular orbit in our analysis below.

### 4. LIGHT-CURVE SOLUTIONS

The light curves of AQ Ser show moderate proximity effects, with the curvature between the minima being mostly due to the deformation of the components and, to a smaller degree, to the mutual illumination. The small but significant difference in depth between the primary and secondary eclipses indicates a slightly cooler temperature for the secondary star, which in this case corresponds to the more massive and presumably more evolved component.

The analysis of the differential photometry of AQ Ser was carried out using a version of the W-D model (Wilson & Devinney 1971; Wilson 1979, 1993) extensively improved as described by Vaz et al. (2007, and references therein). The URSA and NFO light curves were modeled both separately and together, adopting the ephemeris in Equation (1). The orbit was assumed to be circular, based on the evidence from the eclipse timings presented above and from the spectroscopic analysis. The main quantities we adjusted are the orbital inclination angle, \( i \), the temperature of the secondary, \( T_{\text{eff}}^B \), the gravitational pseudo-potentials, \( \Omega \), an arbitrary phase shift, \( \Delta \phi \), and a luminosity normalization factor. The primary temperature was held fixed at the value \( T_{\text{eff}}^A = 6430 \text{ K} \) described in Section 5, and the mass ratio was fixed at the value listed in Table 4. Because the orbital period is short, we assumed both components have their rotation synchronized with the orbital motion. For the bolometric reflection albedos, \( A \), we explored two different treatments: in one we held them fixed at the value of 0.5 appropriate for stars with convective envelopes such as these, and in the other we allowed them to vary freely as the iterations proceeded. The gravity-brightening exponents \( \beta \) were computed using the local value of \( T_{\text{eff}} \) for each point on the stellar surfaces, taking into account mutual illumination following Alencar & Vaz (1997) and Alencar et al. (1999). The radiated flux of both components was described using the PHOENIX atmosphere models (Allard & Hauschildt 1995; Allard et al. 1997; Hauschildt et al. 1997a, 1997b). The luminosity of the secondary was calculated internally from its size and \( T_{\text{eff}} \). All solutions were performed by alternating between the least-squares and simplex methods to improve convergence (see, e.g., Press et al. 1992), with equal weights for all measurements. Iterations were stopped when the corrections to the individual elements were at least one order of magnitude smaller than the formal errors, and they oscillated between positive and negative in consecutive iterations.

Four different limb-darkening laws were investigated: linear, quadratic, square-root, and logarithmic (see Claret 2000). The coefficients for these laws were interpolated from the tables by the above author using a bilinear scheme for the current values of \( T_{\text{eff}} \) and \( \log g \) at each iteration. The results of our initial exploration of the limb-darkening laws are presented in Table 6, in which we used the URSA and NFO data simultaneously. These tests were run both holding the reflection albedos fixed, and allowing them to vary.

Despite the larger freedom of the model when using nonlinear limb-darkening laws, we found that there is relatively little difference in the quality of the fits, and that the linear law gives marginally better solutions. Figure 2 illustrates the effect that the nonlinear limb-darkening laws have on the light curves, relative to the effect of the linear law. The maximum difference for a system such as AQ Ser turns out to be quite small (~5 mmag), which explains why the resulting light elements in Table 6 are rather similar for the various laws. We also note a modest improvement in the solutions when adjusting the bolometric albedos, as opposed to leaving them fixed. The resulting values of \( \beta \) are somewhat smaller than the canonical values. Based on these tests, for the final solutions we chose to adopt the linear limb-darkening law and to allow the albedos to be adjusted.
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Figure 2. Differences between light-curve models that use a nonlinear limb-darkening law and one that adopts the linear law. The linear law results in only ~5 mmag.

Table 6

| i | $T_{\text{eff}}$ | $A_A$ | $A_B$ | $\Omega_A$ | $\Omega_B$ | $\Delta\phi$ | \(\sigma_{\text{mmag}}\) |
|---|---|---|---|---|---|---|---|
| Linear limb-darkening law |
| 81.2553 | 6347.78 | 0.5000 | 0.5000 | 4.7765 | 4.6224 | 1.18 | 9.015/5.487 |
| ±52 | ±66 | Fixed | Fixed | ±14 | ±11 | ±10 | |
| 81.3235 | 6343.17 | 0.4216 | 0.3972 | 4.7777 | 4.6358 | 1.21 | 9.010/5.460 |
| ±76 | ±72 | ±79 | ±73 | ±16 | ±13 | ±12 | |
| Square-root limb-darkening law |
| 81.3498 | 6346.82 | 0.5000 | 0.5000 | 4.7659 | 4.6307 | 1.15 | 9.034/5.507 |
| ±51 | ±66 | Fixed | Fixed | ±14 | ±12 | ±10 | |
| 81.4415 | 6341.77 | 0.4028 | 0.3762 | 4.7664 | 4.6496 | 1.19 | 9.016/5.482 |
| ±77 | ±71 | ±82 | ±75 | ±15 | ±15 | ±10 | |
| Quadratic limb-darkening law |
| 81.3362 | 6342.54 | 0.5000 | 0.5000 | 4.7665 | 4.6291 | 1.14 | 9.033/5.508 |
| ±51 | ±66 | Fixed | Fixed | ±14 | ±12 | ±10 | |
| 81.4319 | 6337.35 | 0.4006 | 0.3722 | 4.7673 | 4.6482 | 1.20 | 9.017/5.477 |
| ±79 | ±71 | ±82 | ±74 | ±16 | ±14 | ±10 | |

Notes. Test solutions for a fixed mass ratio of $q \equiv M_B/M_A = 1.054 \pm 0.011$ (Section 2.2). Phase shifts $\Delta\phi$ are in units of $10^{-4} P$. Uncertainties are given in units of the last significant digit and represent internal errors from the W-D code.

Our final results are presented in Table 7, for the individual solutions to the URSA and NFO data and also for the combined fit. The uncertainties for the individual solutions are the internal errors reported by the W-D code. For the combined fit that we adopt for the remainder of the analysis we have conservatively increased the internal errors by adding in quadrature half of the difference between the parameters for the individual solutions. Also included in Table 7 are the “volume” radii $r_{\text{vol,A}}$ and $r_{\text{vol,B}}$, which are used in the next section to compute the absolute radii of the components.

The observations along with the fitted model are shown in Figure 3, and residuals are displayed in the lower panels. The remaining systematic effects in the light curve are very small, as illustrated by the gray curves in the lower panels representing a running mean of the residuals. There is good agreement between the V-band light ratio from our final combined fit ($\ell_B/\ell_A = 1.088$) and the spectroscopic value of $\ell_B/\ell_A = 1.05 \pm 0.04$ that we reported in Section 2.2, which is in a passband similar to V. This supports the accuracy of our solution, and in particular that of the relative radii.

5. ABSOLUTE DIMENSIONS

Our spectroscopic and photometric analyses lead to the absolute masses and radii for AQ Ser reported in Table 9 below, which have relative uncertainties smaller than 1.8% and 1.1%, respectively. Given the short orbital period of the system we have assumed that each star’s rotation is synchronized with the orbital motion. Our measured $v \sin i$ velocities from Section 2.2 are indeed consistent with the expected synchronous rotational velocities listed in the table, although they do have fairly large uncertainties.

No spectroscopic determination of the metallicity is available for AQ Ser. A rough photometric estimate was derived by means of the calibration for F stars by Crawford (1975) along with the uvby observations in the Strömgren system by Hilditch & Hill (1975), which, however, lack the necessary measurement of the reddening-free index $\beta$. We circumvented this by using an estimate of the interstellar reddening from dust maps following Hakkila et al. (1997), Schlegel et al. (1998), and Drimmel et al. (2003), and an approximate distance of 580 pc (see below).
These three sources give $E(B-V)$ values of 0.011, 0.039, and 0.036 mag, which are insensitive to distance changes of ±100 pc. We adopt the straight average of $E(B-V) = 0.029 ± 0.010$. With this value and the $uvby$ photometry the metallicity inferred for AQ Ser is [Fe/H] ~ -0.19.

As indicated in Section 2.2, the severe line broadening does not permit us to obtain reliable spectroscopic estimates of the effective temperatures of the components. A mean temperature for the system may be derived from standard photometry available in the literature, including $JHK_s$ measurements from Two Micron All Sky Survey (2MASS; Cutri et al. 2003), $V_T$ and $B_T$ from the Tycho-2 catalog (Hog et al. 2000), $V$ and Strömgren $b-y$ as reported by Hilditch & Hill (1975), Johnson B and V from the APASS catalog (Henden et al. 2012), and Johnson–Cousins $V_C$ photometry from The Amateur Sky Survey catalog (Droge et al. 2006). A total of 11, non-independent color indices were formed for which color/temperature calibrations have been established by Casagrande et al. (2010). Appropriate reddening corrections for each of the indices were applied following Cardelli et al. (1989), using the $E(B-V)$ value established above. The resulting temperatures for a metallicity of [Fe/H] = -0.19 are given in Table 8, and their weighted average is $T_{\text{eff}} = 6380 ± 40$ K. We adopt a more conservative error for this analysis of 100 K. The metallicity dependence of the average temperature is very small, assuming solar metallicity would lower it by only 16 K. Based on this mean photometric temperature for the system and a preliminary temperature ratio from our light-curve solutions, we inferred a temperature for the hotter star of $T_{\text{eff}}^B = 6430 ± 100$ K, corresponding to spectral type F5. This is the value employed in our final fits described in Section 4. The temperature derived for the cooler star from our solutions is $T_{\text{eff}}^A = 6340 ± 100$ K, which corresponds approximately to an F6 star. The two temperatures are of course highly correlated with each other, and the temperature difference is much better determined than the absolute values, as it is directly related to the well-measured difference in eclipse depths. We estimate the difference as $\Delta T_{\text{eff}} = 90 ± 20$ K.

Additional quantities listed in Table 9 include the luminosities and the absolute visual magnitudes, for which we adopted bolometric corrections from Flower (1996) with conservative uncertainties of 0.10 mag. Alternate bolometric correction tables such as those of Popper (1980) or Schmidt-Kaler (1982) give very similar results when used with consistent bolometric magnitudes for the Sun (see Torres 2010). The distance to AQ Ser is estimated to be 577 ± 27 pc, based on the combined out-of-eclipse magnitude of $V = 10.575 ± 0.010$ (Hilditch & Hill 1975) and the extinction computed as $A_V = 3.1 × E(B-V)$. Separate distances calculated for the individual components using the measured light ratio agree with the above value within 1 pc, indicating a high degree of internal consistency in the parameters.

6. COMPARISON WITH STELLAR EVOLUTION MODELS

The masses of the AQ Ser components are both in the regime in which stars develop convective cores, and offer a valuable opportunity for a comparison with stellar evolution theory regarding the importance of extra mixing beyond the core, which has been found to be necessary in order to reproduce observations of binary stars and star clusters (see, e.g., Andersen et al. 1990; Chiosi et al. 1992; Chiosi 1999, and references
errors as well as the scatter in the calibrations following Casagrande et al. (2010). Include contributions from the photometry, reddening, and estimated systematic errors as well as the scatter in the calibrations following Casagrande et al. (2010). The metallicity adopted is [Fe/H] = −0.19. In computing the temperatures all photometric indices were corrected for reddening following Cardelli et al. (1989), using \( E(B−V) = 0.029 \pm 0.010 \).

### Notes
Sources are: (1) Henden et al. 2012; (2) Droege et al. 2006; (3) Hilditch & Hill 1975; (4) Cutri et al. 2003; (5) Høg et al. 2000. Temperature uncertainties include contributions from the photometry, reddening, and estimated systematic errors as well as the scatter in the calibrations following Casagrande et al. (2010).

The metallicity adopted is [Fe/H] = −0.19. In computing the temperatures all photometric indices were corrected for reddening following Cardelli et al. (1989), using \( E(B−V) = 0.029 \pm 0.010 \).

### Table 8
Color Indices and Mean Effective Temperatures for AQ Ser

| Index          | Value \(T_{\text{eff}}\) | Source |
|---------------|----------------|-------|
| Johnson \(B−V\) | 0.481 ± 0.057 6388 ± 241 1 |
| Johnson–Cousins \(V−I_C\) | 0.632 ± 0.215 6153 ± 542 2 |
| 2MASS \(V−J\) | 0.949 ± 0.026 6475 ± 103 3, 4 |
| 2MASS \(V−H\) | 1.176 ± 0.025 6392 ± 77 3, 4 |
| 2MASS \(V−K_s\) | 1.235 ± 0.021 6426 ± 71 3, 4 |
| 2MASS \(J−K_s\) | 0.286 ± 0.031 6239 ± 210 4 |
| Tycho \(B_T−V_T\) | 0.556 ± 0.081 6288 ± 267 5 |
| Tycho–2MASS \(V_T−J\) | 1.084 ± 0.062 6296 ± 169 4, 5 |
| Tycho–2MASS \(V_T−H\) | 1.311 ± 0.061 6264 ± 118 4, 5 |
| Tycho–2MASS \(V_T−K_s\) | 1.370 ± 0.060 6307 ± 120 4, 5 |
| Strömgren \(b−y\) | 0.327 ± 0.030 6401 ± 208 3 |

### Notes
Values measured spectroscopically.

The metallicity adopted is [Fe/H] = −0.19. In computing the temperatures all photometric indices were corrected for reddening following Cardelli et al. (1989), using \( E(B−V) = 0.029 \pm 0.010 \).

## Figure 4
Evolutionary tracks for the measured masses of the components of AQ Ser from the Granada models of Claret (2004). The more massive star is represented with a filled circle, and the other with a triangle. The best-fit metallicity for \( \alpha_{\text{ov}} = 0.00 \) (no overshooting) is \( Z = 0.012 \), corresponding to [Fe/H] = −0.20 (\( Z_\odot = 0.0189 \); Grevesse & Sauval 1998). The lower panels show the effect of increasing \( \alpha_{\text{ov}} \) at the same metallicity. An asterisk on the track for the more massive star (left) indicates the best-fit location, and the asterisk on the other track is the expected location of the less massive star at the same age as the other. This illustrates the age discrepancy mentioned in the text.

\[ d_{\text{ov}} = \alpha_{\text{ov}} H_p, \]  
where \( H_p \) is the local pressure scale height at or across the formal edge of the convective core. Figure 4 shows the evolutionary tracks for the measured masses of AQ Ser, and a range of overshooting parameters (assumed to be the same for the two stars) from \( \alpha_{\text{ov}} = 0.00 \) (no overshooting) to \( \alpha_{\text{ov}} = 0.30 \).

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Absolute dimensions

| Parameter | Star A | Star B |
|-----------|--------|--------|
| Mass \(M_\odot\) | 1.346 ± 0.024 1.417 ± 0.022 |
| Radius \(R_\odot\) | 2.281 ± 0.014 2.451 ± 0.027 |
| \(\log g\) (cgs) | 3.8504 ± 0.0094 3.810 ± 0.012 |
| \(v_{\text{rot}} \sin i\) \(\text{km s}^{-1}\) | 67.6 ± 0.4 72.6 ± 0.8 |
| \(v \sin i\) \(\text{km s}^{-1}\) | 59 ± 10 73 ± 10 |
| \(\alpha (R_\odot)\) | 8.370 ± 0.044 |

Radiative and other properties

| Parameter | Star A | Star B |
|-----------|--------|--------|
| \(T_{\text{eff}}\) \(\text{K}\) | 6430 ± 100 6340 ± 100 |
| \(\log L/L_\odot\) | 0.901 ± 0.027 0.939 ± 0.042 |
| \(M_{\text{bol}}\) \(\text{mag}\) | 2.479 ± 0.069 2.38 ± 0.10 |
| \(BC_V\) \(\text{mag}\) | 0.00 ± 0.10 −0.01 ± 0.10 |
| \(M_V\) \(\text{mag}\) | 2.48 ± 0.12 2.39 ± 0.14 |
| \(L_B/L_A\) \(\text{mag}\) | 1.09 ± 0.13 |
| \((L_B/L_A)_V\) | 1.08 ± 0.19 |
| \(E(B−V)\) \(\text{mag}\) | 0.029 ± 0.010 |
| Distance (pc) | 577 ± 27 |

Notes
Star A (photometric primary) corresponds to the hotter and less massive star of the pair.

\( \alpha_{\text{ov}}\) Values measured spectroscopically.

\( \alpha_{\text{ov}}\) Bolometric corrections from Flower (1996), with conservative uncertainties.
temperatures was found for a metallicity of $Z = 0.012$. This corresponds to $[\text{Fe/H}] = -0.20$ in these models, which is very close to our photometric estimate for the system. However, the fit places both stars in the Hertzsprung gap, which is a very rapid and a priori unlikely state of evolution. Furthermore, the models predict the more massive star (filled circle) to be the hotter one, which is the opposite of what we observe. Better agreement with the measured temperature difference would require nearly identical masses (to well within 1%; see below), while our spectroscopic analysis shows them to differ by about 5% (Table 4). The measured mass ratio is therefore inconsistent with a post-main-sequence status for AQ Ser, and this argues for a significant amount of extra mixing. Indeed, only when the overshooting parameter reaches a value near $\alpha_{ov} = 0.30$ is it possible to obtain a better match to the temperature difference at this metallicity (Figure 4, bottom panel), and this places the stars at the very end of the main-sequence phase. Even this fit is unsatisfactory, however, as the models predict different ages for stars of these masses and radii, with the more massive one appearing younger.

We explored this further by considering other published series of stellar evolution calculations, although in this case the overshooting parameter is generally fixed at a value chosen by the modelers and cannot be changed by the user. In the Yonsei–Yale calculations by Yi et al. (2001) overshooting is treated in the same way as the Granada models, and the multiplicative factor $\alpha_{ov}$ ramps up gradually from zero for stars with no convective core to a maximum of 0.20 as the mass increases (see Demarque et al. 2004), and is a function of metallicity. For models with solar metallicity the mass interval over which the overshooting parameter rises from $\alpha_{ov} = 0.00$ to 0.20 is 1.2–1.4 $M_\odot$. The $\log g$ versus $T_{\text{eff}}$ diagram in the top panel of Figure 5 shows the measurements of AQ Ser compared against Yonsei–Yale evolutionary tracks (solid lines) for the measured masses of the components. The metallicity in the models has been adjusted to a value of $Z = 0.0113$ (or $[\text{Fe/H}] = -0.22$, similar to the value inferred using the Granada models) that gives the best fit with the stars just past the point of hydrogen exhaustion. The corresponding $\alpha_{ov}$ values for these masses are approximately 0.20 for the cooler and more massive star and 0.12 for the other. The best-fit isochrone has an age of 3.0 Gyr, and as before, the fit places the stars in the Hertzsprung gap. However, once again there is a problem with the masses. Evolution is such a strong function of mass at these phases that in order to be so close together in this part of the diagram the Yonsei–Yale models require stars of this average mass to have virtually identical masses ($q = 1.0028$). This is in strong disagreement with the measured mass ratio ($q = 1.054 \pm 0.011$) at the 4.6σ level, and excludes such an evolved state. Instead the stars must still be on the main sequence if they are to have the same age, and this implies there must be a significant degree of extra mixing. We illustrate the mass disagreement in the figure in another way by marking the expected location of the two stars on the best-fit isochrone at their measured masses. Theory predicts them to be much farther apart in $T_{\text{eff}}$ and $\log g$ than observed.

An equivalent way of interpreting the discrepancy is in terms of age, as noted earlier. The lower panels of Figure 5 show the predictions from the Yonsei–Yale models for the radius and temperature as a function of mass, along with isochrones for a range of ages. The more massive star is better fit at a younger age than the secondary, the difference being about 0.45 Gyr (or 15%), as seen more clearly in the mass/radius plane. Isochrones in this diagram are mostly vertical for stars of this size, so the significance of the age difference depends largely on the mass separation. The mass uncertainties shown by the shaded boxes represent total errors; the error in the mass difference, $\sigma_{\Delta M}$, is considerably smaller and is also

![Figure 5](image-url)
indicated in the figure. Therefore, the age discrepancy is highly significant.

As mentioned in Section 5, AQ Ser lacks a spectroscopic determination of [Fe/H] and only a photometric estimate is available. While the model comparisons above suggest a metallicity fairly close to that estimate, the solutions are not unique. We find that it is possible to obtain similarly good fits for somewhat lower values of [Fe/H], with the stars being at the end of the main-sequence phase rather than past the “blue hook.” We illustrate this with a third set of models from the Victoria–Regina series (VandenBerg et al. 2006). These calculations use a different description of overshooting based on a parameterized version of the Roxburgh criterion (Roxburgh 1978, 1989; Baker & Kuhfuß 1987), in which the effect is assumed to ramp up between masses of 1.15 and 1.70 $M_\odot$ for compositions near solar. Figure 6 (top) shows a best-fit isochrone in the log $g$ versus $T_{\text{eff}}$ diagram that places the stars in the Hertzsprung gap, but as before it requires a mass ratio very near unity ($q = 1.0008$), at odds with the measured value at the 4.8σ level. This best fit corresponds to an age of 2.9 Gyr and [Fe/H] = −0.20. In the bottom panel an equally good fit is achieved for an age of 2.3 Gyr and [Fe/H] = −0.30 that accommodates the stars on the main sequence with the degree of overshooting prescribed in the models. However, even here theory would require the masses to be nearly the same ($q = 1.0169$) to satisfy the age constraint, which is still in disagreement with the spectroscopic value at the 3.4σ level. Perhaps as importantly, the measured radii or temperatures are not reproduced at the measured masses (see Figure 6). The ages required to match them are again younger for the more massive component, by about the same amount as in the post-main-sequence solution.

A similar exercise with the PARSEC models from the Padova group (Bressan et al. 2012), which employ yet another prescription for overshooting, again allows two qualitatively different solutions. The post-main-sequence scenario strongly disagrees with the measured mass ratio, and a lower metallicity scenario ($Z = 0.0085$ or [Fe/H] = −0.25 for $Z_\odot = 0.01524$; Caffau et al. 2011) with the stars at the end of the main sequence still requires a mass ratio of $q = 1.0153$ that is lower than our spectroscopic result at the 3.5σ level. Thus, all models seem to fail to match the observations for AQ Ser at a single age, pointing to a fundamental problem with theory likely related to overshooting.

7. DISCUSSION

The most common way in which the degree of overshooting has been calibrated in stellar evolution models is by means of star clusters, and in particular through the comparison of isochrones to the blue-hook region in the color–magnitude diagram (CMD). The drawbacks are that this can be affected by contamination of the CMD by field stars, unresolved binary systems, or variable stars, by uncertainties in the chemical composition of the cluster, and even by systematics from the color/temperature transformations. Furthermore, the main property of stars—their absolute mass—is generally not known for any object along the CMD of the clusters most frequently used for this type of comparison. An alternate way of calibrating $\alpha_{\text{ov}}$ is by means of eclipsing binary systems, where masses and radii are precisely known (see, e.g., Ribas et al. 2000). With this method the latter authors found a relatively strong mass (and possibly metallicity) dependence of overshooting for stars in the 2–12 $M_\odot$ range, although subsequent studies reported the mass dependence to be less pronounced and more uncertain (Claret 2007).

The special location of AQ Ser in the H-R diagram makes it a uniquely sensitive test of convective core overshooting in current models of stellar evolution. As shown above, the measured mass ratio is different enough from unity that stars with radii and temperatures as similar as they are in this system cannot possibly be in the post-main-sequence phase. This constitutes clear evidence that mixing beyond the core (overshooting) is required. While early support for the need of extra mixing was

![Figure 6](image-url)
shown nearly 25 years ago by Andersen et al. (1990) from the
inordinately large number of B- and A-type eclipsing systems
that appeared to be in the Hertzsprung gap, the present system
represents a particularly compelling demonstration. However,
AQ Ser shows an additional problem, which is that even with
the inclusion of overshooting and the freedom to adjust the
metallicity in the models so as to accommodate the stars at the
very end of the main-sequence phase, current calculations are
still unable to match the well-measured radius and temperature
difference at the measured masses. Theory requires the stars to
have masses much more similar to each other ($q \approx 1.016$)
than they are observed to be ($q = 1.054 \pm 0.011$), a difference
that seems beyond reasonable observational uncertainties.

This problem manifests itself also as an age discrepancy when
attempting to fit models to each component separately; the
more massive star appears systematically younger. Our
comparisons in the previous section indicate that this difficulty
is common to all models (and the age difference does not
change much compared to the alternate post-main-sequence
fit); the age difference is about 0.5 Gyr for the Granada
models, 0.45 Gyr for the Yonsei–Yale models, and 0.40 Gyr for the Padova models,
all corresponding to 10%–15% of the mean evolutionary age of
the binary. Experiments with the Granada models in which we
varied not only $\alpha$ but also the mixing length parameter $\alpha_M$
individually for each star, for different trial values of $Z$, gave
mean ages ranging from 3.1 to 3.5 Gyr, but did not improve the
situation regarding the age difference. We consistently found
the predicted age for the more massive star to be younger than
the other component.

Similar age discrepancies in the same direction as we see were
pointed out by Clausen et al. (2010) for several other well-
measured F-type eclipsing systems with unequal masses in the
range from 1.15 to 1.70 $M_\odot$. This is roughly the interval in which
the models ramp up the strength of the overshooting, and is also
approximately the mass range in which stars transition from
having their energy production dominated by the p–p chain to
the CNO cycle. The four systems studied by Clausen et al. (2010)
for which age differences were noted are GX Gem, BW Aqr,
V442 Cyg, and BK Peg. Of these, the first is the most similar
to AQ Ser in terms of its evolutionary state. It is located just
prior to the blue hook in the H–R diagram according to the
models, although the component masses are more similar to each
other than those in the AQ Ser system, so the age difference is
less significant. Two other systems studied by us more recently
are also quite near the end of the main sequence: CO And
(Lacy et al. 2010) and BF Dra (Lacy et al. 2012). Although age
anomalies were not mentioned in the original investigations
of these binaries, a closer examination shows that both systems
display age discrepancies similar to those seen previously, with
the more massive component appearing younger. For CO And
the age difference is about 0.3 Gyr (8%), and for BF Dra it is only
$\sim 0.1$ Gyr (4%), but still in the same direction. It is clear from
these observations that a serious deficiency has been uncovered
in current stellar evolution models for this mass range, which
has not previously received much attention beyond the work of
Clausen et al. (2010).

Figure 7 shows the location in the mass/radius diagram of
all well-measured eclipsing binary systems studied by Clausen
et al. (2010), as well as others from Torres et al. (2010) having
both components in the 1.15–1.70 $M_\odot$ range. To these we added
CO And, BF Dra, and AQ Ser. The shaded area represents the
region of the blue hook for solar composition, according to
the Yonsei–Yale models, and an increase in the overshooting
parameter would shift this region upward. AQ Ser is seen to
be the most evolved system in this mass range, which perhaps
explains the larger age discrepancy noted earlier.

Given that overshooting has a direct impact on evolution
timescales, particularly for main-sequence stars in the more
advanced stages, it is natural to suspect that the simplified
treatment of this phenomenon in current models has something
to do with their difficulty in matching the measured properties
of binaries at a single age. However, from our tests with AQ Ser
the explanation does not appear to be a simple difference in $\alpha_M$
for the two components, and may be more complex, involving,
e.g., a dependence of overshooting on the state of evolution,
in addition to mass and metallicity. To our knowledge the
discrepancies highlighted by AQ Ser and the other systems
mentioned above have not been investigated in detail for more
massive stars. Although such a study is beyond the scope of the
present work, it could well provide important clues about the
nature of what we consider one of the outstanding problems of
stellar evolution theory.

We thank P. Berlind, M. Calkins, G. Esquerdo, D. W. Latham,
and R. P. Stefaniak for their assistance in obtaining the spectra
of AQ Ser, and R. J. Davis for maintaining the echelle database
at the Harvard-Smithsonian Center for Astrophysics. We also
thank Dr A. William (Bill) Neely, who operates and maintains
the NFO WebScope, and who handles preliminary processing of
the images and their distribution. We are grateful to the anony-
mous referee for helpful comments. G.T. acknowledges partial
support from this work from NSF grant AST-1007992. L.P.R.V.
gratefully acknowledges partial support from the Brazilian agen-
cies CNPq, FAPEMIG, and CAPES.
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