A PHOTOMETRIC AND SPECTROSCOPIC ANALYSIS OF ECLIPSING BINARY AQ SERPENTIS.

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Introduction: Thanks to the unique properties of close eclipsing binary stars, astronomers are able to analyze these systems to glean information regarding the stars' properties to a degree of accuracy unattainable with other star systems. It is vital that these systems both are eclipsing (to produce useful light curves) and have short orbital periods (to allow for more data points and thus higher accuracy).

Fortunately, binary stars occur with such frequency in the universe that finding these close eclipsing binary stars is not too difficult. AQ Ser was discovered as a variable star by Hoffmeister [1] in 1935. In the past decade, many eclipses (or minima) of AQ Ser had been recorded and the period estimated to be ~1.7 days.

Objective: The immediate goal of this project is to determine all of the fundamental physical and orbital properties of AQ Ser to the best accuracy attainable. This is done by examining its generated light curve (LC) and radial-velocity curve (RV curve), which would be fit to theoretical curves based on certain values of the stars' parameters. Once the absolute properties are confidently known, they are tested against the Yonsei-Yale (YY) models of stellar evolution. Disagreement may require further correction of the models so that stellar evolution can be better understood.

Gathering Data: The observations were taken using Dr. Lacy's URSA (Undergraduate Research Studies in Astronomy) telescope. URSA is a Meade LX200 10" Schmidt-Cassegrain that records images on an SBIG ST-8 CCD camera using a V filter. Operating from June 2003 through May 2007, URSA accumulated more than 3000 images taken in 60 second exposures. The pattern used to identify AQ Ser in the sky was provided by the NFO telescope located in Grant County, New Mexico. Flat field exposures of a blank twilight sky were taken about once per month to minimize the distortion on the CCD camera.

A list of 41 radial velocities was provided by G. Torres (2011, private communication). The spectral types of the stars in AQ Ser were obtained by Kukarkin [2] who determined them to be F7; an uncertainty of two spectral types (F5-F9) was assumed. The spectral type was used to interpolate values for the temperature and visual surface brightness parameter from the table *Radiative Parameters* from Popper [3]. Since there is a considerable difference between spectral types, the temperature and brightness parameters obtained were only preliminary values. The gravitational darkening coefficient was obtained using a theoretical fit by Claret [4] that exhibits a relationship between temperature and gravitational darkening. Temperature and an approximate gravitational constant were used to find a preliminary value for limb darkening via Diaz-Cordoves et. al. [5].

Measuring the data: All images taken by URSA were entered into *Multi-Measure* one night at a time. This program measured the magnitude differences between the variable star, comparison star, and check star. This method is known as differential photometry. It guards against inaccuracies due to the dimness of AQ Ser and accounts for changes in the sky (so that they are not mistaken for actual dimming/brightening of AQ Ser). The magnitudes were then plotted by their Heliocentric Julian Date. Any time an eclipse is recognized by a local minimum in the graph, the data from that night was entered into *Multi-Minima*.

Multi-minima is responsible for producing the light curve (Fig. 1), the most important piece of data in this project. In addition to the 21 minima found, the online source *Simbad* was used to find 11 more minima via Hubscher et. al. [6] [7] and Lacy [8] [9]. *Dates of Minima* and *ephem.best* applications were then used to find an accurate ephemeris of AQ Ser: HJD Min 1 = (1.6874302)n + 53499.5409. This formula can be used to detect any future primary minima.

All the applications mentioned thus far were created by Dr. Lacy.

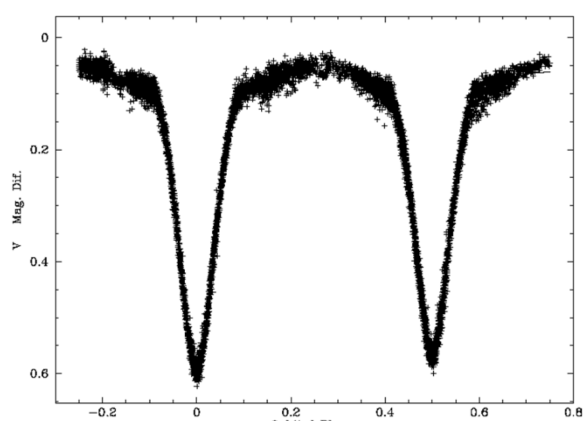

Figure 1: The light curve of AQ Ser. At phase 0, the hotter star is being eclipsed, and at phase 0.5, the cooler star is being eclipsed. The curvature outside of eclipse is due to the tidally distorted shapes of the stars.

Analyzing the Data: *Light curve.* The first step taken in analyzing the newly compiled data was generating a fit to the light curve using the application JKTEBOP (Eclipsing Binary Orbit Program) [10] [11]. This program would change parameter values iteratively until a close fit to the known light curve was found. This program was run multiple times using different combinations of fixed and varying parameters until a low standard error was achieved.

Radial velocity curve. JKTEBOP produced physical properties of the stars, most in ratios, using photometric data. GLSPL (Generalized Least Squares with Plotting) [12] was used to construct a radial velocity curve using the spectroscopic data from G. Torres and output orbital parameters of AQ Ser.

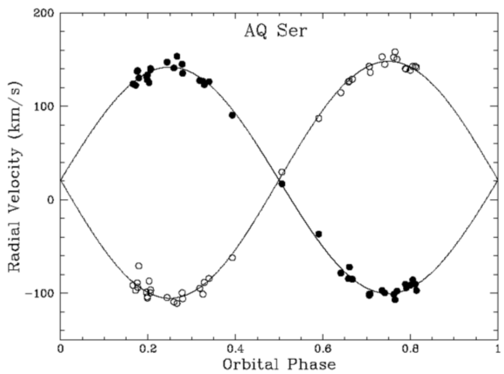

Figure 2: The radial velocity curve. The open circles represent the primary (hotter) star and the filled circles represent the secondary (cooler) star.

Absolute properties. Since JKTEBOP gave most output parameters in ratio form, the program MRLCALC (Mass-Radius-Luminosity Calculator), a program written by Dr. Lacy, was used to determine absolute properties of the two stars given input from JKTEBOP. However, JKTEBOP insisted that there was a third light was present. This raised the concern that the two stars may be in a semi-detached state (close enough for tidal forces to distort the stars' shapes). Thus, a more complete program, *Phoebe* (Physics of Eclipsing Binaries) [13], which could account for such systems, was used.

YY models. The final step in the analysis was to use the program *YYtrack* to map the evolutionary tracks of the two stars on a plot similar to an H-R diagram but with luminosity replaced by gravitational constant (g). According to the YY models, the evolutionary track of the stars in the binary system along this diagram is only dependent on mass, radius, and metallicity [14]. The procedure of creating a fit of this diagram with each star was done by iteratively changing the metallicities (which were assumed to be the same for each star).

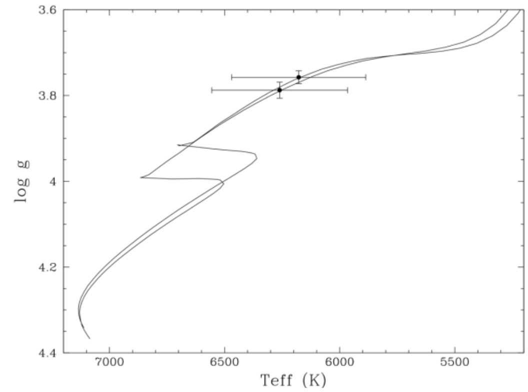

Figure 3: YY plot, which includes main sequence and post-main sequence, where the two stars reside.

Results: The absolute properties found by MRLCALC and *Phoebe* are given below. *Phoebe* did not provide any uncertainties, but all of its values are within the uncertainty of the MRLCALC results. All values are in solar units except log(g) (cm/s^2).

	MRLCALC	**Phoebe**
Mass(p)	1.305 (± 0.022)	1.308
Mass(s)	1.364 (± 0.024)	1.364
R(p)	2.415 (± 0.032)	2.428
R(s)	2.556 (± 0.022)	2.570
Log(g) p	3.787 (± 0.011)	3.784
Log(g) s	3.757 (± 0.007)	3.754
Log(L) p	0.908 (± 0.076)	0.969
Log(L) s	0.934 (± 0.075)	0.943

Conclusion: The primary aspect of the YY models that this project tested is the idea that any two stars in a close binary system must have formed at approximately the same time from the same star-forming region. The ages of the stars were found to be within 6% of each other, within the limit of the 10% constraint set by the YY models, further confirming the theory.

Interestingly, the stars were found in post-main sequence, which constitutes a very small portion of a star's lifetime and should therefore be quite rare. To check, 49 binary stars were analyzed using *YYtrack*. Only 3 were determined to be in post-main sequence.

References: [1] Hoffmeister, C. (1935) *Astr. Nachr.*, 255, 401. [2] Kukarkin, B.V. (1969) *General Catalogue of Variable Stars*, Third Edition. [3] Popper, D.M. (1980) *Ann. Rev. Astron. Astrophys.*, 18, 115. [4] Claret, A. (1998) *A & AS*, 131, 395. [5] Diaz-Cordoves, J., Claret, A., & Gimenez, A. (1995) *AAS*, 110, 329-350. [6] Hubscher J., Paschke A., Walter F. (2005) *IBVS*, 5657. [7] Huebscher, J. (2007) *IBVS*, 5802. [8] Lacy C.H.S. (2006) *IBVS*, 5670. [9] Lacy C.H.S. (2007) *IBVS*, 5764. [10] Popper & Etzel (1981) *AJ*, 86, 102. [11] Etzel (1981) *psbs.conf*, 111E. [12] Daniels W.E. (1966) *Univ. of Maryland Phys. Astron. Tech. Report*, No. 579. [13] A. Prša and T. Zwitter 2005 *ApJ*, 628, 426. [14] Yi Sukyoung et.al. (2001) *Astr. Journ. Supp. Ser.*, 136, 2, 417-437.