Spectroscopic and Photometric Study of the Eclipsing Binary Star σ Aquilae

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Received January 22, 2023; revised March 31, 2023; accepted March 31, 2023

Abstract We report on spectroscopic and photometric observations of the eclipsing binary star σ Aquilae (44 Aql). Archival TESS and Hipparcos data are used to confirm the orbital period of 1.95028 ± 0.00002 days, consistent with previous measurements. Doppler shifts of the He I line at 4922 Angstroms from high-resolution spectroscopic data were used to model the system's orbital motion. From this we were able to determine a mass ratio of the two stars of M2 / M1 = 0.79, an inclination angle of the orbital plane of i = 72 degrees, masses of M1 = 5.8 $M_{\odot}$ and M2 = 4.6 $M_{\odot}$, and radii of 3.7 and 3.3 solar radii, respectively. The mass ratio is consistent with previous results, but we note that our derived masses are lower by approximately 5–10% with respect to most of the previous studies.

1. History

Many studies have been conducted on the variable σ Aquilae in the modern age of astronomy; below, we report the most significant for the purposes of our study. The star is cataloged as an eclipsing binary star in the GCVS (Samus *et al.* 2017) with B3V+B3V type star components. The variable radial velocity of σ Aql was discovered at Mount Wilson in 1912, and the spectroscopic orbit was published by Jordan (1916) with a period of 1.95022 d, circular orbit (e = 0), K1 = 163.52 km, K2 = 199 km, m1 $\sin^3(i)$ = 5.3 $M_{\odot}$, and m2 $\sin^3(i)$ = 4.4 $M_{\odot}$. The first photoelectric light curve was obtained by Wylie (1922) with a period of 1.95026 d. Spectroscopic observations by Luyten *et al.* (1939) showed an orbital period of 1.950272 d, while Koch *et al.* (1965) found the spectral types B3+B4 for the components of this binary system with an orbital inclination sin i = 0.949 (71.6°). Cester *et al.* (1978) reported an orbital period of 1.9503 d, orbital inclination of 72.2°, q ratio of 0.79 with masses of 6.8, 5.4 $M_{\odot}$, radii of 4.22, 3.05 solar radii, spectral types B3+B3, and a T = 18950 K for the hotter component. Brancewicz and Dworak (1980), using an iterative numerical method and data collected from several sources, determined a q ratio of 0.86 and a mass of 5.70 $M_{\odot}$ for the more massive star. The radii determined are 3.75 and 3.32 solar radii for each star Brancewicz and Dworak 1980). Hoffleit and Jaschek (1991) reported in the *Bright Star Catalogue* that the spectral type of the two component stars is B3V+B3V. Pan *et al.* (1998) calculated a perfectly circular orbit (e = 0).

2. Instrumentation and methodology

Observations were made near the Bassano Bresciano Astronomical Observatory (45° 19' 32" N, 10° 07' 49" E) (WGS84[1]) with a home-made 0.4-m Schmidt telescope operating at an effective focal ratio of f/10. Both the telescope and the home-made dome were operated remotely to make the observations presented here; Figure 1 shows the telescope, with its horseshoe equatorial mount, and the dome.

The telescope is controlled using custom software written in C++ and called POLYPUS 2.0. It controls the operations of the telescope and instrumentation, including pointing, tracking, and taking exposures.

Spectra were secured with the ATHOS spectrograph that was made for high-resolution spectroscopy (Figure 2). It is a Littrow-type spectrograph operating at the same focal ratio as the telescope. The effective focal length of the acromat doublet of the spectrograph is 180 mm with a diameter of 25 mm. The spectrograph is equipped with 12 slits of 10, 20, 30, 40, 50, 70, 100, 150, 200, 300, 500, and 700 uM width. The diffraction grating has 2400 lines per mm and the images are secured with a StarlightXpress Trius-SX9 CCD camera, which has a sensor area of 1392 × 1040 pixels (pixels are 6.45 uM square).

Slit width used for the observations is 20 uM and, in order to maximize the signal-to-noise ratio, we have used the CCD binned 2 × 2. With this configuration the spectral resolution is about R = 10000 in the range 4822–4980 Å and a dispersion of 0.18 Å / pixel. For calibration purpose the spectrograph is equipped by a RELCO starter lamp placed in front of the slit.

Sources were targeted only above 30° elevation, both so that nearby trees would not get in the way and because atmospheric extinction and refraction significantly degrade the images at and above airmass values of about 2. Three types of images were secured for each observing run: images of the target were made at exposure times of 300 s to ensure good signal-to-noise in the final spectra, dark frames were taken at the same exposure time after each night of observing, and flat field images were secured using an external halogen lamp shining on a white panel that is attached to the inside of the dome.

The software package ISIS version 6.1.1 (Buil 2021) was used to reduce the data and extract the stellar spectra in an automated way. The software package PERANSO 3 (Paunzen

[1] WGS84—World Geodetic System 1984 (also known as EPSG:4326) is a worldwide geodetic geographic coordinate system based on a reference ellipsoid developed in 1984.

Figure 1. Observations were obtained using home-made 0.4-m Schmidt telescope operating at an effective focal ratio of f/10, equipped with Starlight Xpress Trius-SX9 CCD.

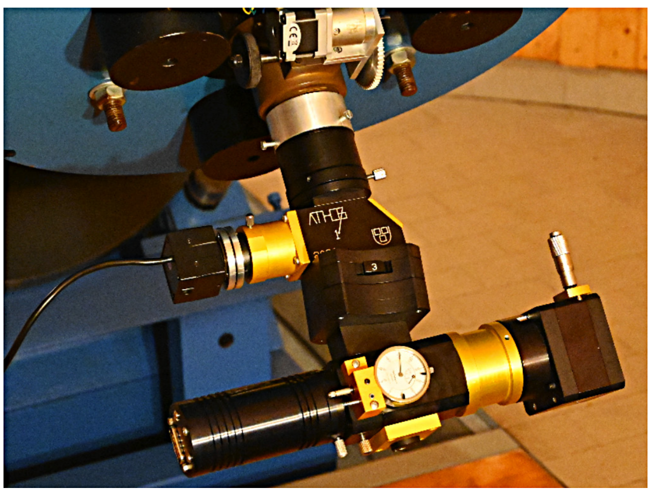

Figure 2. ATHOS is a home-made spectrograph equipped with a 2400-line grating and rotating slits.

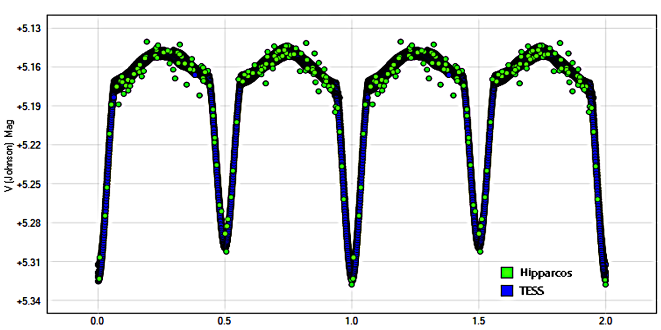

Figure 3. Light curve of σ Aql derived from Hipparcos and TESS data, folded with a period of 1.95028 d.

Table 1. Time of minima for σ Aquilae from TESS data.

Time of Minima	*Eclipse Type*
2459770.1410 ± 0.0013	primary
2459771.1148 ± 0.0012	secondary
2459772.0901 ± 0.0010	primary
2459773.0644 ± 0.0013	secondary
2459774.0397 ± 0.0010	primary
2459783.7929 ± 0.0010	primary
2459784.7668 ± 0.0010	secondary
2459785.7419 ± 0.0014	primary
2459786.7165 ± 0.0012	secondary
2459787.6908 ± 0.0009	primary
2459788.6667 ± 0.0011	secondary
2459789.6418 ± 0.0013	primary
2459795.4935 ± 0.0014	primary

and Vanmunster 2016) was used to create the photometric light curve and determine the period of variability.

3. Photometric data

We used Hipparcos (Perryman *et al.* 1997) and TESS (TASC 2023) data, via the "Internet light curve plotting" function implemented in Peranso. For all imported data the HJD correction was applied. To the TESS data an appropriate offset was applied to the magnitudes in order to minimize the differences in relation to the Hipparcos data. The period analysis was carried out with ANOVA algorithm, implemented in Peranso, on all imported data, for a more precise period determination. The resulting period is 1.95028 ± 0.00002 d, accepted by the VSX, in place of the previous period of 1.950269 d. From TESS data we obtained eight primary minima and five secondary minima measurements (Table 1). The center of eclipses and the Epoch (2459787.6908 HJD) was determined by a fifth-degree polynomial using Peranso. Figure 3 shows the light curve obtained from Hipparcos and TESS data folded with a period of 1.95028 days.

4. Spectroscopic data

We observed σ Aql spectroscopically for 24 nights, from 2022 Aug 19 to 2022 Sep 22, obtaining a set of 45 spectra, each stacking seven raw images of 300 s in order to improve the signal and to minimize errors. Before stacking each raw image was calibrated with dark and flat frames. For each set of seven spectra a relative calibration lamp image was obtained. All spectra were corrected for heliocentric velocity before wavelength measurements were made.

Since σ Aql is a blue star, we performed the measurements in λ using the He I line (λ 4922 Å) which presents a clear doubling due to the Doppler-Fizeau effect (see Figure 4).

The radial velocities were derived from the λ measurement (Å) performed with Peranso software and a fifth degree polynomial fit on both halves of the double-line He I of each spectrum, obtaining a total of 59 (41+18) λ values for the two stars. From the λ measurements we calculated the radial velocities using the following formula:

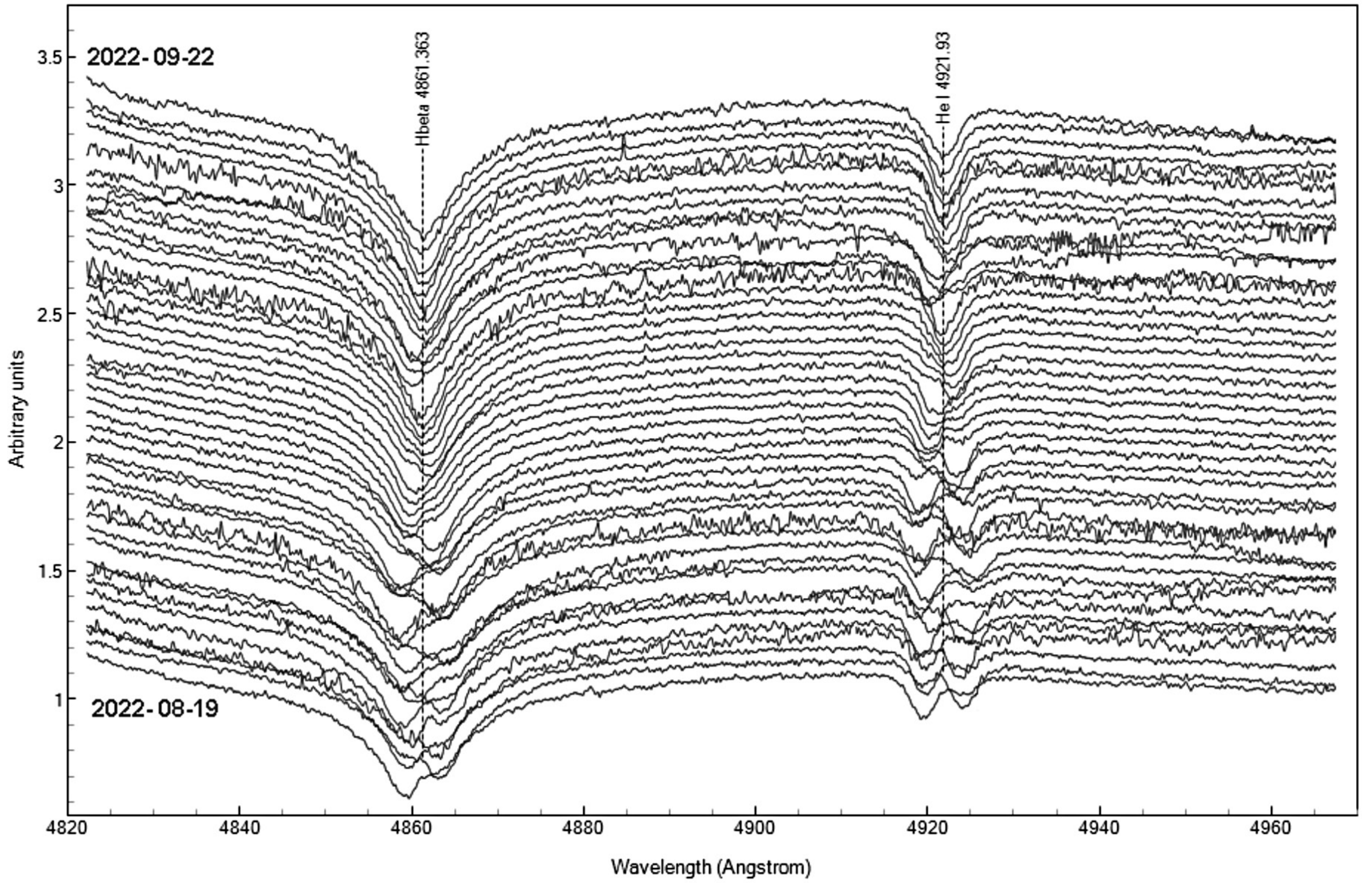

Figure 4. The spectra acquired from 2022 08 19 to 2022 09 22 show the evolution of the double-peaked Hβ and He I absorption lines. This last was used for the radial velocity measurements.

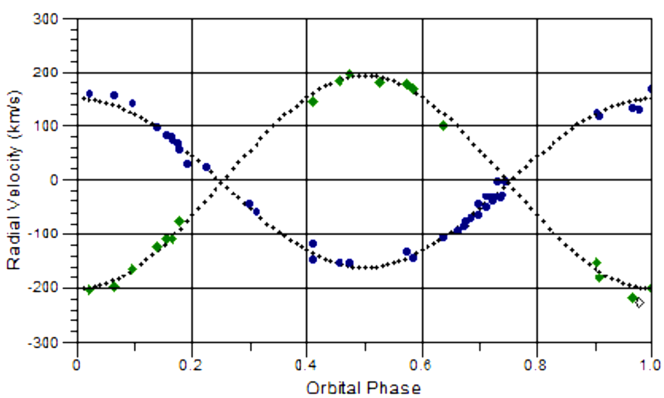

Figure 5. Orbital phase for σ Aql obtained from radial velocity data and plotted with SBS software.

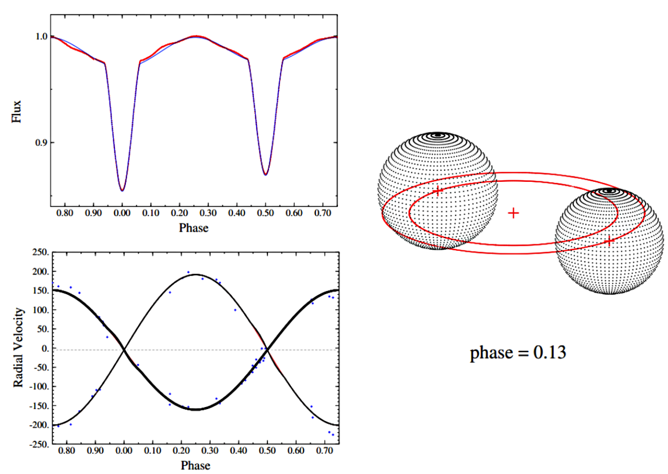

Figure 6. Model of the σ Aql system obtained with Binary Maker 3.

$$\mathrm{RV(km/s)} = \frac{\Delta\lambda}{\lambda 0}\,c, \quad (1)$$

where $\Delta\lambda$ is the measured shift in wavelength of a given spectral line, $\lambda 0$ is the rest wavelength of a spectral line, and c is the speed of light in a vacuum (299792.458 km/s).

The Spectroscopic Binary Solver (SBS) software version 1.4 (Johnson 2004) was used to estimate the relevant orbital parameters of the binary system σ Aql.

For more detailed information about the use of SBS software see the user manual installed with the software and references therein. All derived radial velocities were arranged into a text file, according to the SBS-required file format for double-line observation data.

A typical SBS session performs in succession the functions: Read File, Period, Solve, and Error Est. The period was fixed to 1.95028 d (from photometric data) and a circular orbit was assumed (e = 0). By means of the function Solve the software automatically solves for the orbital parameters via the Downhill Simplex method implemented into the SBS software. Once the orbital parameters were obtained, the Error Est. function made it possible to obtain the estimate of the uncertainties. The summary of parameters produced is shown in Table 2.

Table 2. Parameter summary of the orbital elements derived by SBS fsoftware for the binary system σ Aquilae.

Parameter	*Summary*
Semi-Amplitude K(1)	156.192 ± 2.880 km/s
Semi-Amplitude K(2)	196.673 ± 3.126 km/s
Systemic Velocity	–4.8323 ± 1.4679 km/s
Mass ratio	0.79
Orbital Period	1.95028 days
Time of Periastron	2459809.62504 ± 0.00399 HJD
a1 sin (i)	4.1888e+06 ± 7.72e+04 km
a2 sin (i)	5.2744e+06 ± 8.38e+04 km
m1 $\sin^3$ (i)	4.9484e+00 ± 7.87e-02 $M_\odot$
m2 $\sin^3$ (i)	3.9298e+00 ± 7.25e-02 $M_\odot$

Table 3. Final parameters used for modeling the binary system σ Aquilae with Binary Maker 3.

Parameter	*Value*
q (mass ratio)	0.79
i (inclination angle, deg)	71.97
r1 (relative radius [back])	0.257
r2 (relative radius [back])	0.231
T1 (K)	19050
T2 (K)	17860

Table 4. Absolute masses, semi-major axis of the orbit, and stellar radii of σ Aql.

Parameter
M1 = 4.9484 / $\sin^3$(i) = 5.8 ± 0.1 solar masses
M2 = 3.9298 / $\sin^3$(i) = 4.6 ± 0.1 solar masses
a = $(74.5 * P2 * (M1+M2))^{1/3}$ = 14.3 ± 0.1 solar radii
(P is the orbital period in days)
R1 = 0.257 * a = 3.7 solar radii
R2 = 0.231 * a = 3.3 solar radii

5. Modelling

To model the σ Aql binary system, the software Binary Maker 3 (Bradstreet and Steelman 2002) was used with a subset of TESS photometric data. Assuming the mass ratio of the system as the ratio of the two radial velocity semi-amplitudes, the value derived from SBS analysis was q = K1/K2 = M2/M1 = 0.794171. The primary star temperature has been assumed as T = 19050 K, on the basis of the spectral type B3V from log T_{eff} = 4.280 (Pickles 1998). The eccentricity was assumed to be circular (e = 0), on the basis of previous studies reported in section 1.

The model parameters have been derived using an iterative approach, changing the fractional radii of the two components and the inclination of the binary system towards the Earth observer's line of sight, in order to minimize the sum square of the residual of the model fit. The final parameters used for the model are shown in Table 3.

From the orbital elements and inclination we can derive the absolute masses of the components, the semi-major axis of the orbit, and the stellar radii, which are shown in Table 4.

6. Discussion

We report in Table 5 the current findings on σ Aql, comparing them with the previously published results. The T_{eff} of the hotter component used for our model is close to the one published by Cester *et al.* (1978). The orbital period falls within 0.001% of the other results and the orbital inclination is close to the other published values within 0.5%. In general, the masses and radii we have found are a little smaller than those reported in most of the previous studies. However, it should be noted that there is an excellent correspondence with the values found by Brancewicz and Dworak (1980), which used a computational method on existing data, except for the q ratio with respect to which we note a difference of –8%, caused by the lower mass of the secondary star. This circumstance could imply the need to review the spectral classification of the components of the binary system.

We must also consider that the high precision of the TESS light curve implies constraints on transit/occultation times that lead us to exclude the ratios of the radii k = 1.0 and k = 0.72 reported respectively by Wylie (1922), Luyten *et al.* (1939), and Cester *et al.* (1978). The fit of the TESS light curve remains very good, with a ratio of the radii k = 0.90, as in the model we have adopted.

7. Conclusions

We present updated physical parameters for the eclipsing binary star σ Aql using archival photometric data and high-resolution spectroscopy secured at Osservatorio Astronomico Bassano Bresciano. The mass ratio determined for this system is consistent with previous results. Our masses are a little lower than most previously published results, but close to the results obtained by Brancewicz and Dworak (1980). We have an exception for the mass of the secondary star which may indicate

Table 5. Summary of the principal elements of σ Aquilae as reported in different studies.

	Jordan (1916) *Wylie (1922)*	*Luyten* et al. (1939)	*Koch* et al. (1965)	*Cester* et al. (1978)	*Brancewicz* et al. (1980)	*This Study*
Spectral type	B8+B8	—	B3+B4	B3+B3	B3V+B3V	B3V+B3V
T_{eff} primary (K)	—	—	—	18950	16840	19050
Period (days)	1.95026	1.950272	1.95	1.9503	1.950260	1.95028
i (°)	71.7	—	71.6	72.2	—	71.97
e	0	0	—	—	—	0
q (M2/M1)	0.83	0.79	—	0.79	0.86	0.79
M1 ($M_{\odot}$)	6.19	6.8	—	6.8	5.70	5.8
M2 ($M_{\odot}$)	5.14	5.4	—	5.4	4.90	4.6
k (R2/R1)	1.0	1.00	—	0.72	0.89	0.90
R1 ($R_{\odot}$)	3.9	3.66	—	4.22	3.75	3.7
R2 ($R_{\odot}$)	3.9	3.66	—	3.05	3.32	3.3
a ($R_{\odot}$)	14.7	15.1	—	—	14.43	14.3

the need to revise the spectral class so, we recommend follow-up observations to clarify this point. The constraints on light curve fit led us to exclude the ratios of the radii very different from k = 0.90, which we have adopted for our model. This work was a major test of the data taken at Bassano Bresciano using the ATHOS spectrograph: they show us that it is possible to present results that are of scientific quality using home-made equipment that will be useful to the wider astronomical community.

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