Absolute Dimensions and Evolutionary Status of the Semi-detached Algol W Ursae Minoris

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Abstract

Double-lined eclipsing binaries allow accurate and direct determination of fundamental parameters such as mass and radius for each component, and they provide important constraints on the stellar structure and evolution models. In this study, we aim to determine a unique set of binary parameters for the Algol system W UMi and to examine its evolutionary status. New high-resolution time-series spectroscopic observations were carried out during 14 nights from 2008 April to 2011 March, and a total of 37 spectra were obtained using the Bohyunsan Optical Echelle Spectrograph. We measured the radial velocities (RVs) for both components, and the effective temperature of the primary star was found to be $T_{\text{eff,1}} = 9310 \pm 90$ K by a comparison of the observed spectra and the Kurucz models. The physical parameters of W UMi were derived by an analysis of our RV data together with the multi-band light curves of Devinney et al. The individual masses, radii, and luminosities of both components are $M_1 = 3.68 \pm 0.10 M_\odot$ and $M_2 = 1.47 \pm 0.04 M_\odot$, $R_1 = 3.88 \pm 0.03 R_\odot$ and $R_2 = 3.13 \pm 0.03 R_\odot$, and $L_1 = 102 \pm 1 L_\odot$ and $L_2 = 7.3 \pm 0.1 L_\odot$, respectively. A comparison of these parameters with theoretical stellar models showed that the primary component lies in the main-sequence band, while the less massive secondary is noticeably evolved. The results indicate that the initially more massive star became the present secondary by losing most of its own mass via mass transfer to the companion (present primary).

Key words: binaries: eclipsing – binaries: spectroscopic – stars: evolution – stars: fundamental parameters – stars: individual (W UMi)

1. Introduction

Algol systems are generally semi-detached interacting binaries that are composed of a hotter and more massive main-sequence primary star and a Roche-lobe-filling giant/subgiant secondary of F-K spectral type (Giuricin et al. 1983; Sarna 1993). They may be produced from initially detached binaries by tidal interaction and mass transfer between the two components, which have evolved differently to single stars. The originally more massive star evolves past the terminal-age main sequence (TAMS) and overflows its limiting lobe, while the gainer becomes the current primary component by accreting the mass transferred via the Lagrange $L_1$ point. Thus, semi-detached Algols are important for understanding the formation and evolution of stellar systems, as well as astrophysical phenomena such as mass transfer and accretion between component stars, angular momentum loss via magnetic stellar winds, and magnetic activity in the cool companion (Ibanoglu et al. 2006; Erdem & Öztürk 2014). For their study, we need to precisely determine the absolute properties of both components in these systems through a detailed analysis of both multi-band light curves and double-lined radial velocity (RV) data. If the two kinds of observations are of good quality, mass and radius measurements can be achieved with accuracies better than about 1%, which are used as tests of stellar evolutionary theory and as distance indicators (Torres et al. 2010).

W UMi (BD+86 244, TYC 4651-61-1, 2MASS J16082718+8611595) is an Algol-type eclipsing binary with an orbital period of 1.7011 day. It was reported to show photometric variability by Astbury (1913) and also Dyson (1913). The spectroscopic observations of the binary star were seen as single-lined by Joy & Dustheimer (1935) and Sahade (1945). The former authors classified the spectral type of the primary component as A4, and determined its velocity semi-amplitude and systemic velocity to be $K_1 = 105.5$ km s$^{-1}$ and $\gamma = -7.7$ km s$^{-1}$, respectively. On the contrary, the latter author obtained different velocities of $K_1 = 86.6$ km s$^{-1}$ and $\gamma = -17.7$ km s$^{-1}$. He presented that the primary component is an A3 star with a rotational velocity of $\sim 40$ km s$^{-1}$ and a small eccentricity of $e = 0.09$. However, Lucy & Sweeney (1971) preferred to adopt a circular orbit in their discussion of the Sahade’s data. From the Hipparcos, ASAS, and NSVS data, Kreiner et al. (2008) reported that the binary system is in a circular orbit, and its eccentricity is probably spurious.

On the other hand, Devinney et al. (1970) reviewed the observational history of the stellar system prior to 1970 and separately analyzed two sets of light curves observed in $BV$ filters at the Flower and Cook Observatory (hereafter, $B_{FC}$, $V_{FC}$) and in $UBV$ filters at the Dyer Observatory (hereafter, $U_D$, $B_D$, $V_D$). They found that the photometric parameters ($i \approx 84 \deg$, $r_2/r_1 \approx 0.78$) for the two data sets agreed very well with each other. The spectral type of the primary component was classified as A3 $\pm 2$ from the color indices of $(U - B)$ and $(B - V)$, which is in good agreement with the spectroscopic classifications. Since then, Mardirossian et al. (1980) and Djurasevic et al. (2003) re-analyzed the photometric data of Devinney et al. (1970), and both of them presented a mass ratio of $q_{ph} \approx 0.48$. Although the same data were used in the light-curve synthesis, Devinney et al. (1970) and Mardirossian et al. (1980) reported that W UMi is in detached or semi-detached configurations, while Djurasevic et al. (2003)
showed that the eclipsing binary is a semi-detached system with the secondary component filling its inner Roche lobe.

As previously mentioned, although several photometric studies of W UMi were made by analyzing the multi-band light curves of Devinney et al. (1970), there are no RVs for the secondary component. Hence, the spectrophotometric mass ratio and the reliable absolute dimensions have not been established so far. The main purpose of this study is to present the precise physical properties of the Algol system and to examine its evolutionary state based on our new time-series spectroscopy and on the existing photometric data. The remainder of this paper is organized as follows. In Section 2, we describe new spectroscopic observations and data analysis of our program target. The absolute dimensions of each component are determined from the binary modeling in Section 3. In Section 4, the results are summarized and the evolutionary state is discussed.

2. Observations and Data Analysis

New spectroscopic observations were made on 14 nights between 2008 April and 2011 March using the 1.8 m telescope at the Bohyunsan Optical Astronomy Observatory (BOAO). We obtained a total of 37 spectra using the Bohyunsan Optical Echelle Spectrograph (BOES) attached to the telescope, which is designed to cover the wavelength region of 3600–10200 Å. More information about the specifications of the BOES can be found in the paper of Kim et al. (2007). We used a resolving power ($\lambda/\Delta\lambda$) of 30000 with the largest fiber of 300 μm diameter. The observed spectra were acquired with an exposure time of 2700 s, and they were pre-processed with the IRAF/CCDRED package and extracted to one-dimensional spectra with the IRAF/ECHELLE package. The typical signal-to-noise ratio (S/N) at 5000–6000 Å was approximately 40.

To measure the RVs for the primary and secondary stars in the observed spectra, we searched for absorption lines that were strong enough that both components could be clearly identified. Although the temperature difference between them is large ($\Delta T \approx 3800 \text{ K}$) and the luminosity contribution of the secondary star to the W UMi system is very low (Djurasevic et al. 2003), we found that the isolated line of Fe I 4957.61 Å in our spectra shows the spectral line from the faint secondary. Some series spectra in the Iron region are shown in Figure 1. The RVs of each component were determined using the line profile fitting with two Gaussian functions (Hong et al. 2015), and the resultant RVs and their errors are listed in Table 1.

The effective temperature ($T_{\text{eff}}$) and the projected rotational velocity ($\langle v_1 \sin i \rangle$) of the primary star were determined by the $\chi^2$ fitting method (Guo et al. 2016; Hong et al. 2017), which is used to minimize the difference between observed spectra and theoretical stellar atmosphere models. As mentioned in the Introduction, the primary component of W UMi was classified as an A-type star from its single-lined spectra and color indices. Thus, we selected the Fe I $\lambda 4046$, Fe I $\lambda 4957$, Ca I $\lambda 4427$, and Mg II $\lambda 4481$ regions proper for temperature indicators of A-type dwarfs according to the Digital Spectral Classification Atlas of R. O. Gray.6 First of all, we used the spectral disentangling code FDBinary (Ilijić et al. 2004) to obtain the reconstructed spectra of the four regions from all observed spectra. Then, 5850 synthetic spectra with ranges of $T_{\text{eff}} = 8760–10250 \text{ K}$ and $\langle v_1 \sin i \rangle = 96–134 \text{ km s}^{-1}$ were interpolated from the grids of atmosphere models by Kurucz (1993). For this process, the solar metallicity of [Fe/H] = 0 and a microturbulent velocity of $2.0 \text{ km s}^{-1}$ were assumed. The surface gravity of the primary component was set to be $\log g_1 = 3.8$ from our binary solutions, which is obtained in the following section. Finally, we calculated the $\chi^2$ values between the reconstructed and synthetic spectra in these regions, and the search results are shown in Figure 2. The best-fitting parameters were determined to be $T_{\text{eff},1} = 9310 \pm 90 \text{ K}$ and $\langle v_1 \sin i \rangle = 105 \pm 6 \text{ km s}^{-1}$, respectively, and their errors were calculated from the standard deviations of the best values obtained in each region. The observed spectra of Fe II $\lambda 4046$, Fe I $\lambda 4957$, Ca I $\lambda 4427$, and Mg II $\lambda 4481$ are presented in Figure 3, together with three synthetic spectra of 9400 K, 9310 K, and 9220 K, respectively.

Because the secondary star contributes only a few percent to the total luminosity of the W UMi system, and the S/N of the observed spectra were not enough, it is difficult to reconstruct the spectrum of the cool component and to directly obtain its atmospheric parameters. Therefore, we checked the atmospheric parameters of the secondary star by comparing the observed spectra with the synthetic spectra computed from the temperature of $T_{\text{eff},2} = 5370$ K and the surface gravity of $\log g_2 = 3.6$ presented in Section 3. The results are shown in Figure 1, where the blue and red lines indicate the synthetic spectra of the primary and secondary stars, respectively. As seen in the figure, the observed spectra are in satisfactory agreement with the synthetic spectra of both components.

3. Binary Modeling and Absolute Dimensions

To obtain the binary parameters of W UMi, our double-lined RV curves were analyzed together with the $(BV)_0$ light curves of Devinney et al. (1970) using the 2003 version of the Wilson-Deviney synthesis code (Wilson & Devinney 1971; van Hamme & Wilson 2003; hereafter W–D). In this paper, we refer to the primary and secondary components as those being eclipsed at Min I (phase 0.0) and Min II, respectively. The effective temperature of the hotter and more massive primary star was fixed at $T_1 = 9310 \text{ K}$ from our spectral analyses. We adopted the gravity-darkening exponents and bolometric albedoes for each component to be $(g_1, A_1) = (1.0, 1.0)$ and $(g_2, A_2) = (0.32, 0.5)$, which are appropriate for stars with radiative and convective envelopes, respectively. Linear bolometric $(X, Y)$ and monochromatic $(x, y)$ limb-darkening coefficients were interpolated from the values of van Hamme (1993) in concert with the model atmosphere option. Recently, Kreiner et al. (2008) proposed the existence of a circumbinary object in the system from an eclipse timing analysis. Thus, we looked for a possible third light ($\ell_3$), but we found that the parameter remains zero within its error. We set the third light to be $\ell_3 = 0$ for further analyses.

The time gap between the photometric and spectroscopic data used in our synthesis is very long, and the orbital period has varied due to a sinusoidal variation superposed on a downward parabola (Kreiner et al. 2008). Thus, the analyses of these data sets were separately performed in two steps, following the procedure described by Hong et al. (2015) and Koo et al. (2016). In the first step, our double-lined RV curves were modeled by adjusting the epoch ($T_0$), the orbital period ($P$), the semimajor axis ($a$), the systemic velocity ($\gamma$), and the

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6 More information is available on the website (https://ned.ipac.caltech.edu/level5/Gray/frames.html).
mass ratio \((q)\), where the orbital ephemeris were initialized with the linear elements calculated from the eclipse timings of W UMi. In the second step, we analyzed the multi-band light curves of Devinney et al. (1970) with the spectroscopic elements obtained in the first stage. These steps were repeated until the binary parameters of W UMi were unchanged. Our binary modeling started from the detached mode 2 but converged to the semi-detached mode 5 (the secondary filling its inner Roche lobe) during the computation. The final results are listed in Table 2, where \(r\) (volume) is the mean volume radius calculated from the tables of Mochnacki (1984). Figure 4 shows the RV curves of W UMi with the model fits, wherein the measurements from Joy & Dustheimer (1935) and Sahade (1945) are plotted together for comparison. Figure 5 displays the \((BV)_{\text{FC}}(UBV)_{\text{D}}\) light curves of Devinney et al. (1970) with the W–D fits.

Our RV and light solution indicates that W UMi is a semi-detached Algol with parameters of \(q = 0.399, i = 86.0^\circ\), and \(\Delta(T_{\text{eff},1} - T_{\text{eff},2}) = 3944\) K, where the primary star fills its Roche lobe by 77\%. From the consistent set of binary parameters, the absolute dimensions for each component were calculated using the JKTABSDIM code (Southworth et al. 2005), and they are listed in Table 3. The luminosity \((L)\) and bolometric magnitudes \((M_{\text{bol}})\) were computed by the adoption of \(T_{\text{eff},1} = 5780\) K and \(M_{\text{bol},1} = +4.77\) for solar values. For the absolute visual magnitudes \((M_{V})\), we used the bolometric corrections \((BCs)\) from Girardi et al. (2002) appropriate for the effective temperatures of each component. The mass \((M_1 = 3.68 M_{\odot})\) of the primary star is much heavier than that \((\sim 1.5 M_{\odot})\) of normal main-sequence stars with the same effective temperature, but is compatible with the mass–luminosity relation of \(L_1 \propto M_1^{3.20}\) for the semi-detached binaries given by İbanoğlu et al. (2006).

This may be because W UMi has experienced a different evolutionary process than single stars through the secondary to primary mass transfer.

Using an apparent visual magnitude of \(V = 8.61\) at maximum light (Kreiner et al. 2008) and an interstellar absorption of \(A_V = 0.382\) from the Galactic 3D model (Drimmel et al. 2003), we computed the distance of the W UMi system to be 488 ± 10 pc. This result is in excellent agreement with the value of 506 ± 63 pc obtained by the trigonometric parallax (1.98 ± 0.25 mas) from Gaia DR1 (Gaia Collaboration et al. 2016).

### 4. Summary and Discussion

In this article, high-resolution time-series spectroscopic observations were presented for the Algol system W UMi. We analyzed in detail the new spectra with existing photometric data. The results from this work can be summarized as follows:

1. From the observed spectra, we detected an isolated absorption line \((\text{Fe I} 4957.61\) Å) of the cool secondary star and measured the RVs of both components; the

| HJD (2450000+) | Phase | \(V_1\) \((\text{km s}^{-1})\) | \(\sigma_1\) \((\text{km s}^{-1})\) | \(V_2\) \((\text{km s}^{-1})\) | \(\sigma_2\) \((\text{km s}^{-1})\) |
|----------------|-------|-----------------|-----------------|-----------------|-----------------|
| 4568.0616     | 0.440 | −52.6           | 2.5             | ...             | ...             |
| 4568.1053     | 0.466 | −37.7           | 3.1             | ...             | ...             |
| 4568.1481     | 0.491 | −25.5           | 4.6             | ...             | ...             |
| 4570.9995     | 0.167 | −93.9           | 1.3             | 184.2           | 1.6             |
| 4571.0423     | 0.192 | −102.8          | 3.4             | 187.3           | 5.8             |
| 4571.0852     | 0.217 | −99.3           | 1.7             | 197.7           | 1.4             |
| 4571.1277     | 0.242 | −103.9          | 1.2             | 179.5           | 8.4             |
| 4571.1714     | 0.268 | −101.6          | 0.8             | 197.5           | 3.9             |
| 4572.0157     | 0.764 | 65.9            | 1.3             | −222.2          | 8.8             |
| 5281.2352     | 0.692 | 68.7            | 1.3             | −216.2          | 1.4             |
| 5281.2670     | 0.711 | 73.4            | 3.0             | −211.0          | 2.7             |
| 5281.2996     | 0.730 | 73.6            | 1.1             | −213.1          | 1.8             |
| 5281.3313     | 0.749 | 71.0            | 2.0             | −201.3          | 2.4             |
| 5282.2880     | 0.311 | −99.4           | 1.2             | 175.9           | 3.3             |
| 5282.3198     | 0.330 | −102.1          | 5.1             | 178.1           | 2.4             |
| 5284.2744     | 0.479 | −26.3           | 1.2             | ...             | ...             |
| 5284.3062     | 0.498 | −15.6           | 1.1             | ...             | ...             |
| 5578.3414     | 0.352 | −96.9           | 1.9             | 170.5           | 0.9             |
| 5578.3733     | 0.371 | −86.2           | 2.8             | ...             | ...             |
| 5579.3014     | 0.916 | 26.7            | 1.2             | ...             | ...             |
| 5579.3652     | 0.954 | 25.8            | 1.3             | ...             | ...             |
| 5628.2076     | 0.667 | 64.4            | 1.8             | −197.0          | 3.2             |
| 5628.2393     | 0.685 | 67.7            | 2.3             | −211.1          | 4.2             |
| 5628.2710     | 0.704 | 72.8            | 2.1             | −220.9          | 2.2             |
| 5629.1863     | 0.242 | −103.9          | 3.5             | 184.7           | 5.2             |
| 5629.2180     | 0.261 | −106.1          | 2.1             | 180.8           | 3.6             |
| 5629.2499     | 0.279 | −105.1          | 2.6             | 187.4           | 6.8             |
| 5629.2816     | 0.298 | −102.3          | 4.2             | 194.5           | 1.9             |
| 5630.1983     | 0.837 | 46.9            | 3.8             | −192.8          | 7.0             |
| 5630.2300     | 0.856 | 59.9            | 2.4             | −177.2          | 4.7             |
| 5630.2619     | 0.874 | 57.1            | 0.9             | −171.4          | 3.6             |
| 5631.0028     | 0.310 | −95.1           | 1.6             | 169.1           | 6.5             |
| 5632.1817     | 0.003 | −3.6            | 4.2             | ...             | ...             |
| 5633.1746     | 0.587 | 27.3            | 1.1             | ...             | ...             |
| 5633.2063     | 0.605 | 35.9            | 1.1             | ...             | ...             |
| 5633.2380     | 0.624 | 47.8            | 2.8             | ...             | ...             |
| 5633.2699     | 0.643 | 51.1            | 2.1             | −203.5          | 4.1             |
Figure 2. $\chi^2$ diagrams of the effective temperature ($T_{\text{eff},1}$) and the projected rotational velocity ($v_\text{sini}$) of the primary star.

Figure 3. Four spectral regions of the primary star. The circles are the spectrum observed at an orbital phase of $\phi = 0.50$. The blue, red, and green lines represent the synthetic spectra of 9400 K, 9310 K, and 9220 K, respectively, from the atmosphere models of Kurucz (1993).
Figure 4. RV curves of W UMi with fitted models. The filled and open circles represent our double-lined RV measurements for the primary and secondary components, respectively. The square and diamond symbols represent the single-lined RVs of Joy & Dustheimer (1935) and Sahade (1945), respectively. In the upper panel, the solid curves denote the results from a consistent light and RV curve analysis with the W–D code. The dotted line represents the system velocity of $-15.4$ km s$^{-1}$. The lower panel shows the residuals between observations and theoretical models.

Table 2

| Parameter | Primary | Secondary |
|-----------|---------|-----------|
| $T_0$ (HJD) | 2439758.8456 ± 0.0001 |  |
| $P$ (day) | 1.7011577 ± 0.00000001 |  |
| $i$ (deg) | 86.0 ± 0.1 |  |
| $T$ (K) | 9310 ± 90 | 5366 ± 17 |
| $\Omega$ | 3.139 ± 0.003 | 2.677 |
| $\Omega_{in}$ | 2.677 |  |
| $l/(l_1+2l_2)_{BC}$ | 0.9675 ± 0.0009 | 0.3025 |
| $l/(l_1+2l_2)_{HC}$ | 0.9340 ± 0.0005 | 0.0660 |
| $l/(l_1+2l_2)_{BO}$ | 0.9764 ± 0.0009 | 0.0236 |
| $l/(l_1+2l_2)_{BO}$ | 0.9675 ± 0.0007 | 0.0325 |
| $l/(l_1+2l_2)_{BO}$ | 0.9340 ± 0.0005 | 0.0660 |
| $r$ (pole) | 0.3618 ± 0.0004 | 0.2824 ± 0.0003 |
| $r$ (point) | 0.3958 ± 0.0007 | 0.4069 ± 0.0015 |
| $r$ (side) | 0.3750 ± 0.0005 | 0.2944 ± 0.0004 |
| $r$ (back) | 0.3857 ± 0.0006 | 0.3270 ± 0.0004 |
| $r$ (volume) | 0.3745 ± 0.0005 | 0.3025 ± 0.0004 |

Spectroscopic orbits:

| Parameter | Primary | Secondary |
|-----------|---------|-----------|
| $T_0$ (HJD) | 2454385.300 ± 0.013 |  |
| $P$ (day) | 1.701060 ± 0.0000019 |  |
| $a$ ($R_\odot$) | 10.355 ± 0.093 |  |
| $\gamma$ (km s$^{-1}$) | -16.4 ± 1.1 |  |
| $K_1$ (km s$^{-1}$) | 87.6 ± 1.3 |  |
| $K_2$ (km s$^{-1}$) | 219.5 ± 2.3 |  |
| $q$ | 0.399 ± 0.009 |  |

2. The effective temperature and the projected rotational velocity of the primary star were determined to be $T_{\text{eff},1} = 9310 \pm 90$ K and $v_1 \sin i_1 = 105 \pm 6$ km s$^{-1}$, respectively, by minimizing the $\chi^2$ values between the reconstructed and synthetic spectra in four regions. The measured velocity indicates that the primary star may be in a synchronous rotation ($v_{1,\text{sync}} = 115.3 \pm 1.0$ km s$^{-1}$) with the orbital motion. On the other hand, it is difficult to obtain the atmospheric parameters of the secondary star, because the S/N of the observed spectra and the light ratio of the components are low. Thus, we compared the photometric results of $q_{\text{ph}} \approx 0.48$ (Mardirossian et al. 1980; Djurasevic et al. 2003). Because it was obtained from the double-lined RV curves, our $q$ value should be more accurate and reliable than that obtained from only the photometric data.
Figure 6. Positions on the HR diagram for W UMi (star symbols) and other semi-detached Algols (circles, Ibanoglu et al. 2006). The filled and open symbols represent the primary and secondary stars, respectively. The red and blue lines denote the conservative evolutionary track for a binary with a total mass of 4.2 $M_\odot$ (De Loore & van Rensbergen 2005).

observed spectra with the synthetic spectra from the models, our program target, it is thought that W UMi has undergone significant evolution. The HR diagram of Figure 6, together with the mass and luminosity, together with the mass and luminosity, and with the conservative evolutionary track of a binary star, consisting of a mass donor component (low-mass progenitor) of 3.0 $M_\odot$ and its companion (present primary) of 1.2 $M_\odot$ with an initial orbital period of 2.0 day (De Loore & van Rensbergen 2005). As shown in Figure 6, the primary (P) and secondary (S) components of W UMi are a good match to the conservative binary evolution model. Further, they lie on the same isochrone with the present age of about 0.36 Gyr. Although the binary evolution tracks are not for a stellar system with the same total mass of 5.15 $M_\odot$ as our program target, it is thought that W UMi has undergone conservative binary evolution through a case-A mass transfer between the component stars. On this account, the present primary star was formed by mass accretion from the initially more massive component, and the donor star became the evolved low-mass secondary star by transferring most of its own mass to the gainer (present primary).

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