Modified Masses and Parallaxes of Close Binary Systems: HD 39438 Postprint

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We present the detailed fundamental stellar parameters of the close visual binary system HD 39438 for the first time. We used Al-Wardat's method for analyzing binary and multiple stellar systems. The method implements Kurucz's plane parallel model atmospheres to construct synthetic spectral energy distributions (SEDs) for both components of the system. It then combines the results of the spectroscopic analysis with the photometric analysis and compares them with the observed ones to construct the best synthetic SED for the combined system. The analysis gives the precise fundamental parameters of the individual components of the system. Based on the positions of the components of HD 39438 on the H-R diagram, and evolutionary and isochrone tracks, we found that the system belongs to the main sequence stars with masses of 1.24 and 0.98 solar masses for the components A and B, respectively, and age of 1.995 Gyr for both components. The main result of HD 39438 is new dynamical parallax, which is estimated to be 16.689 ± 0.03 mas.

Full Text

Modified Masses and Parallaxes of Close Binary Systems: HD 39438

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Abstract

We present for the first time the detailed fundamental stellar parameters of the close visual binary system HD 39438. We employed Al-Wardat's method for analyzing binary and multiple stellar systems, which implements Kurucz's plane-parallel model atmospheres to construct synthetic spectral energy distributions (SEDs) for both components. The method combines spectroscopic analysis with photometric analysis and compares them with observed measurements to construct the best synthetic SED for the combined system. This analysis yields precise fundamental parameters for the individual components. Based on the positions of HD 39438's components on the H-R diagram and evolutionary isochrone tracks, we find that the system consists of main-sequence stars with masses of 1.24 and 0.98 solar masses for components A and B, respectively, and an age of 1.995 Gyr for both components. The primary result for HD 39438 is a new dynamical parallax estimated to be 16.689 ± 0.03 mas.

Key words: methods: analytical – techniques: photometric – (stars:) binaries: visual – techniques: spectroscopic

1. Introduction

Understanding binary stars represents one of the most vital disciplines in contemporary stellar astronomy. Close binary systems are particularly valuable for precisely estimating fundamental stellar parameters, especially stellar masses, as up to 50% of all systems exist in binary or multiple configurations (Duquennoy et al. 1991). Modern techniques of speckle interferometry (Balega et al. 2002a; Tokovinin et al. 2010; Köhler 2014) and adaptive optics (Roberts et al. 2005; Roberts 2011) have proven instrumental in studying and analyzing close visual binary systems. The analysis of spectroscopic and astrometric data assumes paramount significance in the era of speckle interferometry and adaptive optics (Lucy 2018), and these techniques are essential for advancing our understanding of binary evolution and relative motion.

Al-Wardat's method for analyzing binary and multiple stellar systems (BMSSs) merges spectroscopic and photometric analysis results with observed measurements, representing the most effective approach for such systems (Al-Wardat 2002, 2003, 2007). This method consolidates magnitude difference measurements from speckle interferometry, combined spectral energy distributions from spectrophotometric analysis using ATLAS9 model grids (Kurucz 1994), and radial velocity measurements (when available) to estimate individual fundamental stellar parameters and determine precise spectrophotometric masses. The method has been extensively utilized to compare synthetic stellar photometry with observed photometry for solar-type stars (Al-Wardat 2009, 2012, 2014; Al-Wardat et al. 2014a, 2014b, 2014c, 2016, 2017, 2021a; Masda et al. 2016, 2018a, 2018b, 2019a, 2019b, 2021; Widyan & Aljboor 2021; Yousef et al. 2021). Synthetic stellar photometry, which involves analyzing spectroscopic results (synthetic SEDs) of binary systems, enables more precise determination of fundamental parameters through comparison with observations (Al-Wardat et al. 2014a, 2014b, 2021a; Masda et al. 2018a, 2018b, 2019a, 2019b, 2021; Widyan & Aljboor 2021), thereby contributing to improved characterization of close binary systems.

In this work, we study the visual close binary HD 39438 (HIP 27758) in the solar neighborhood. The system has been reported at parallaxes of $\pi\{H07\} = 20.15 \pm 1.19$ *mas (van Leeuwen 2007) and* $\pi\{\mathrm{DR3}\} = 16.0508 \pm 0.264$ mas (Gaia Collaboration 2022), where astrometric measurement abbreviations are detailed in Masda & Al-Wardat (2023). However, the renormalized unit weight error for π_{DR3} was very large, rendering this solution unsuitable for our analysis.

The first orbital calculation for this binary was solved by Mason et al. (2010) with a grade of three (G3 = Reliable). They found a dynamical stellar mass of 0.44 M based on van Leeuwen (2007) parallax and 0.34 M based on Gaia DR3 parallax. Tokovinin et al. (2014) subsequently revised the orbit, also with grade three, calculating a dynamical stellar mass. Tokovinin (2017) later revised the orbit again, upgrading it to grade two (G2 = Good), which should be adopted. In that study, individual dynamical masses were estimated as 1.29 M and 0.97 M for the primary and secondary components, respectively, with a system dynamical mass of 2.26 M. Based on these results, Tokovinin (2017) indicated that the van Leeuwen (2007) parallax was inaccurate and required revision, suggesting a new dynamical parallax of π_{dyn} = 17.6 mas.

Building upon Masda & Al-Wardat (2023), which presented modified masses and parallaxes for a selected sample of close binary systems, this paper has three primary aims: first, to publish the fundamental stellar parameters of HD 39438 using Al-Wardat's method for analyzing BMSSs; second, to compare observed photometry of the combined system with synthetic photometry; and third, to report spectrophotometric stellar masses and a new dynamical parallax for the system.

This paper is organized as follows: Section 2 presents the observational data for HD 39438, Section 3 describes the analysis method, Section 4 explains the stellar mass calculation procedure, Section 5 provides results and discussion, and Section 6 concludes the study.

2. Observed Data

Observed data form the backbone of synthetic analysis. Photometric data from various sources serve as key references for obtaining stellar parameters, including the Hipparcos (ESA 1997), Strömgren (Hauck & Mermilliod 1998), and Tycho catalogs (Høg et al. 2000), which we compare with synthetic photometric data to study the system in detail. Table 1 lists the basic data and observed photometry of HD 39438, while Table 2 contains the observed magnitude differences between the primary and secondary components.

3. Method and Analysis

The spectrophotometric analysis represents the most important step in Al-Wardat's method, which employs two solutions to estimate astrophysical parameters:

3.1. Spectroscopic Solution

The spectroscopic solution is the key to producing fundamental stellar parameters. In this solution, we construct synthetic SEDs for both the combined system and individual components. First, we require the observed magnitude difference of the system, estimated as Δm = 1.49 ± 0.01, which represents the average of all Δm measurements under V-band filters given in Table 2. This observed magnitude difference, combined with the visual magnitude, yields the individual apparent and absolute magnitudes for the primary and secondary components through the following relationships:

m_A = V - 2.5 log(1 + 10^(-0.4Δm)) m_B = m_A + Δm M = m - 5 log(d) + 5

where d is the distance to the system in parsecs. Since HD 39438 is a nearby system, interstellar extinction is neglected.

The absolute magnitudes of HD 39438's components are employed to estimate input parameters, along with introductory values from Lang (1992) and Gray (2005). For main-sequence stars, we use the following equations:

log(g) = log(M/M) - log(R/R) + 4.44 T_{eff} = 5777 K (for reference) M_{bol} = M_V + BC

where BC is the bolometric correction.

Individual synthetic SEDs for each star are built based on these input parameters. We employ Kurucz ATLAS9 models—plane-parallel model atmospheres developed by Kurucz (1994)—to generate synthetic fluxes for individual components. When combined with the parallax, these produce the synthetic SED for the close binary system. For this purpose, specialized subroutines of Al-Wardat's method for analyzing BMSSs must be utilized. The combined synthetic SED is determined using:

$$F\_\lambda = (R\_A^2\ F\_\lambda,A + R\_B^2\ F\_\lambda,B)\ /\ d^2$$

where F_λ is the combined synthetic SED, R_A and R_B are the radii of components A and B in solar units, and F_λ,A and F_λ,B are the corresponding fluxes in units of ergs $cm^{-2}\ s^{-1}\ Å^{-1}$. These individual fluxes depend on $T\_\{eff\}$ and log g, and the equation accounts for the energy flux from both components located at distance d (in parsecs) from Earth.

The radius values in this equation depend primarily on the accuracy of parallax measurements. Tokovinin et al. (2000) demonstrated that parallax measurements of binary systems can be distorted by orbital motion, which explains why significant problems emerged when applying Al-Wardat's method to binary system parallaxes, necessitating new dynamical parallax values (Al-Wardat et al. 2021b; Masda & Al-Wardat 2023). The fundamental stellar parameters must remain consistent with observed binary system properties, representing one of the best methods for ensuring parallax accuracy. Therefore, we calculate the synthetic photometric solution to determine the optimal stellar parameters for the close visual binary system.

3.2. Photometric Solution

The synthetic photometric solution perfectly complements the spectroscopic solution and is instrumental in estimating fundamental stellar parameters of close binary systems. Its primary aim is to calculate magnitudes and color indices for both combined and individual synthetic SEDs and compare them with observations in any photometric system. Synthetic magnitudes and color indices are calculated for Johnson (U, B, V, R, U−B, B−V, V−R), Strömgren (u, v, b, y, u−v, v−b, b−y), and Tycho (B_T, V_T, B_T−V_T) systems using:

$$m\_p = -2.5 \log[\ P\_p(\lambda)F\_\lambda,s(\lambda)d\lambda\ /\ \ P\_p(\lambda)F\_\lambda,r(\lambda)d\lambda] + ZP\_p$$

where m_p is the synthetic magnitude in passband p, $P\_p(\lambda)$ is the dimensionless sensitivity function for passband p, $F\_\lambda,s(\lambda)$ is the synthetic SED of the object, and $F\_\lambda,r(\lambda)$ is the SED of the reference star (Vega). Zero-point values (ZP_p) from Maíz Apellániz (2007) are adopted.

4. Mass and Dynamical Parallax

Stellar mass plays a vital role in understanding binary system formation and evolution, requiring accurate estimation. Two mass types are considered: spectrophotometric mass ($M\_\{Sph\}$) and dynamical stellar mass (M_d). The former is estimated from evolutionary tracks using Al-Wardat's method for analyzing BMSSs, while the latter is determined from the orbital solution based on Kepler's third law:

$$M\_A + M\_B = a^3\ /\ (\pi^3\ P^2)$$

where a and π are the semimajor axis and parallax (both in arcseconds), P is the orbital period (in years), and M_A and M_B are the masses (in solar masses).

The error in dynamical mass is estimated through standard error propagation.

Dynamical masses depend primarily on orbital grade quality. We adopt the best available orbit with grades of: Grade 1 = Definitive, Grade 2 = Good, and Grade 3 = Reliable. When spectrophotometric mass agrees with dynamical mass, the system parallax is adopted; otherwise, it must be estimated using Al-Wardat's method:

π{dyn} = (a / P^(2/3)) / (M{Sph},A + M_{Sph},B)^(1/3)

where M_{Sph} are the spectrophotometric masses estimated via Al-Wardat's method (in solar masses) and π_{dyn} is in arcseconds. Its error is estimated through appropriate error propagation.

5. Results and Discussions

We estimated the fundamental stellar properties of the close binary system HD 39438 using Al-Wardat's complex analytical method (Al-Wardat 2002), which combines spectroscopic and photometric solutions to determine physical and geometrical parameters, leading to a new parallax value for the system. Table 3 lists the calculated synthetic magnitudes and color indices for individual components and combined synthetic SEDs across different photometric systems (Johnson: U, B, V, R, U−B, B−V, V−R; Strömgren: u, v, b, y, u−v, v−b, b−y; Tycho: B_T, V_T, B_T−V_T).

Table 4 demonstrates excellent agreement between synthetic and observed photometry for HD 39438, confirming that the basic stellar characteristics listed in Table 5 are reliable. Table 3 shows that synthetic apparent magnitudes are completely consistent with observed apparent magnitudes.

The stellar luminosities of HD 39438's components are estimated as L_A = 2.65 ± 0.08 L and L_B = 0.76 ± 0.09 L for the primary and secondary, respectively. The spectral types are F5.5V and G8V, consistent with Mason et al. (2010) and Tokovinin (2017), and with the F5V classification in the WDS and SIMBAD catalogs.

Based on our analysis, Figure 1 [Figure 1: see original paper] presents for the first time the adopted combined synthetic SED and individual component SEDs, established through optimal agreement between observed and synthetic stellar photometry.

Figure 2 [Figure 2: see original paper] displays the spectrophotometric stellar masses of HD 39438, determined using Al-Wardat's complex method with Girardi et al. (2000b) evolutionary tracks and the system's fundamental parameters. These masses are 1.24 ± 0.11 M and 0.98 ± 0.09 M for the primary and secondary components, respectively. According to Tokovinin (2017), the total system mass is 2.26 M based on spectral types, which agrees with our result of 2.22 M .

The total dynamical mass from Mason et al. (2010) orbital solutions (2.56 ± 0.32 M) is consistent with our total mass within error margins, though no agreement exists between Al-Wardat's method results and the dynamical mass from Tokovinin et al. (2014). However, Tokovinin (2017) revised the orbit with improved parameters, grading the new orbital solution as two (G2 = Good), which is more accurate than previous versions. That study presented a new parallax of π_{dyn} = 17.6 mas based on the revised orbital solution, though this measurement requires further observational refinement.

Our analysis employed Tokovinin (2017)'s dynamical parallax and good orbital solution (P = 11.963 ± 0.036 yr and a = 0. 1207 ± 0. 0007) to calculate a dynamical mass sum of 2.22 ± 0.05 M , which aligns well with the spectrophotometric mass sum (ΣM = 2.22 M) from Al-Wardat's method. We conclude that the suggested dynamical parallax should be slightly larger than Tokovinin (2017)'s value. Consequently, using Tokovinin (2017)'s good orbital solution and our spectrophotometric mass sum (ΣM = 2.22 M), we computed a new dynamical parallax of π_{dyn} = 17.689 ± 0.03 mas—the closest estimate to Tokovinin (2017)'s value. We anticipate that future Gaia data will provide improved trigonometric parallax measurements.

Figure 2 shows both components' positions on Girardi et al. (2000a) isochrone tracks, revealing a metallicity of [Z = 0.019, Y = 0.27] for HD 39438. Based on these isochrones, the system age is 1.995 Gyr. The combined system metallicity is 0.015 based on observed data (Gáspár et al. 2016), which corresponds well with the synthetic metallicity of 0.019 shown in Figure 2.

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