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The stellar system HIP 101227: is it a binary, a triple or a quadruple system?

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Abstract In this paper, we present the analysis of the stellar system HIP 101227 to determine the actual number of components in the system, and their properties. We use dynamical modeling and complex spectrophotometric (involving atmospheric modeling) techniques with recent data, to determine the physical properties and orbital solution for the system, respectively, with better accuracy than past studies. Based on our analysis, we found that the system is more consistent with being a quadruple rather than a binary or a triple system as suggested by previous studies. The total mass of the system determined from our SED analysis is $3.42 \pm 0.20\ M_{\odot}$, which is distributed almost equally between the four stars. The stars are found to be zero-age main sequence stars; i.e., at the last stage of pre-main sequence, with age less than 200 Myr and spectral types K0. All four stars have very similar physical characteristics, suggesting that the fragmentation process is the most likely theory for the formation and evolution of the system.

Key words: stars: binaries: close — stars: binaries: visual — stars: individual: HIP 101227

1 INTRODUCTION

Most of the stars in our Universe are believed to be part of binary or multiple stellar systems (Duquennoy & Mayor 1992). The study of these objects is crucial for testing the formation and evolutionary models of stars. This is because they can provide us with direct measurements of stellar masses (e.g., through dynamical modeling), which is the key property that determines the life cycle of stars. The vast majority of these systems discovered so far are close visual binary and multiple stellar systems (CVBMSs). This means that they appear as a single star even with the largest ground-based telescopes due to their very close separation; i.e., $< 0.5''$ (e.g., Hilditch 2001). This type of stellar system can only be identified applying high-resolution observational techniques such as speckle interferometry (e.g., Labeyrie 1970; Balega & Tikhonov 1977) and adaptive optics.

One of the most common methods used to study the properties of binary stellar systems is photo-dynamical modeling. In this technique, the physical and orbital properties of the stars are obtained by modeling the light curves of binary systems during eclipse (Borkovits et al. 2016, 2019; Koçak et al. 2020; Sürgit et al. 2020). This method, however, can only be used for eclipsing binary systems, which are relatively rare.

In 2002, Al-Wardat (2002) introduced a novel method to determine the complete physical properties of CVBMSs through spectral energy distribution (SED) modeling; i.e., atmospheric modeling. The data required for this technique are the magnitude differences obtained from speckle interferometry measurements and color indices. These data are widely accessible, and therefore the technique can be employed to study the properties of all types of CVBMSs, including face-on orbital binaries. This method can be utilized even in the absence of orbital information and spectroscopic data of the systems. These make it an ideal technique to study the properties of these systems. A series

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Table 1 Basic Properties of HIP 101227

Properties	Parameters	Value	Reference
Position	Right Ascension	$20^{\mathrm{h}}31^{\mathrm{m}}07^{\mathrm{s}}.77$	SIMBAD
	Declination	$+33°32'34''.45$	SIMBAD
Magnitude [mag]	Visual Magnitude (m_{v})	8.34	esa (1997)
	B-V (Johnson)	0.88 ± 0.01	esa (1997)
	Visual Extinction(A_{v})	3.71	Schlafly & Finkbeiner (2011)
	B (Tycho)	9.45 ± 0.02	Høg et al. (2000)
	V (Tycho)	8.44 ± 0.01	Høg et al. (2000)
Parallax (π) [mas]	old	22.38 ± 1.16	esa (1997)
	new	20.47 ± 0.95	van Leeuwen (2007)

of papers that determine the complete set of physical and orbital properties of CVBMSs using this method and dynamical modeling technique developed by Tokovinin (1992), respectively, has been published for many systems (e.g., Al-Wardat 2007; Al-Wardat & Widyan 2009; Al-Wardat 2009; Al-Wardat 2012; Al-Wardat et al. 2014a; Al-Wardat et al. 2014b; Al-Wardat et al. 2016; Masda et al. 2016; Al-Wardat et al. 2017; Masda et al. 2018; Masda et al. 2019a; Masda et al. 2019b). These analytical papers aim at taking advantage of CVBMSs in estimating the key properties of stellar components which are crucial in understanding the formation and evolution of the systems.

In this paper, we will present the SED and orbital modelings of the triple stellar system candidate HIP 101227 (Tokovinin 2018; Dommanget & Nys 2002). This system is part of our study of the brightest ($V \leq 10$ mag) and closest ($d \leq 100$ pc) triple stellar system candidates in our Universe. Our aim for this project is to determine the true nature of the systems; i.e., whether or not they are indeed triple systems, and to study their physical and orbital properties. These are important for having a better census of CVBMSs in general.

HIP 101227 is located at a right ascension of $20^{\mathrm{h}}31^{\mathrm{m}}07^{\mathrm{s}}.77$, and declination of $+33°32'34''.45$ (SIMBAD catalog). The parallax of the system obtained from the Hipparcos New Astrometric Catalog (van Leeuwen 2007) is 20.47 ± 0.95 mas, which corresponds to a distance of 48.85 ± 0.05 pc. In Table 1, we present the basic information for the system. Based on the Multiple Star Catalog by Tokovinin (2018) and Catalog of Components of Double & Multiple Stars by Dommanget & Nys (2002), the system is suggested to be a triple system. However this has not been confirmed, and the system has only been analyzed as a binary in previous literatures.

Malkov et al. (2012) derived the total mass of the system, assuming that it is a binary, utilizing dynamical, photometric and spectroscopic techniques. The total masses determined from these techniques were $1.03 \pm 0.31\ M_{\odot}$, $1.82\ M_{\odot}$ and $0.85\ M_{\odot}$, respectively. The orbit of the system has previously been determined by Docobo & Ling (2006) considering positional measurements obtained from the Fourth Catalog of Interferometric Measurements of Binary Stars.[1] Since then, there have been several new positional measurements for the system. We will rely on these new data in this paper to obtain a more accurate orbital solution for the system. In addition, we will also try to determine the true nature of the system; i.e., whether it is a binary or multiple system, and measure the physical properties of each star in the system.

Table 2 Magnitude Difference Measurements (Δm) for HIP 101227 in Different Filters of the Visual Band

Filter ($\lambda/\Delta\lambda$)	Δm	Telescope diameter [m]	Reference
511 nm/222 nm	0.48 ± 0.12	0.3	esa (1997)
503 nm/40 nm	0.28 ± 0.15	3.5	Horch et al. (2004)
545 nm/30 nm	0.41 ± 0.03	6.0	Balega et al. (2006)
541 nm/88 nm	0.17	3.5	Horch et al. (2008a)
550 nm/40 nm	0.63	3.5	Horch et al. (2010)

2 METHODS

2.1 SED Modeling

In this section, we describe the synthetic SED modeling of the HIP 101227 system following the Al-Wardat (2002) technique in order to estimate the physical properties of each star in the system; i.e., the effective temperatures (T_{eff}), radii (R), gravitational accelerations (log g), luminosities (L), masses, ages and spectral types (S_{p}). We performed the SED modeling by first assuming that the system is a binary, and then a multiple system.

In order to build individual SED models for the system's components, we first calculated the average value for the magnitude difference between the two main components of the system (Δm) in the V-band. All of the magnitude difference measurements for HIP 101227 in the V-band are tabulated in Table 2. The average value calculated from these data is $\Delta m = 0.39 \pm 0.16$.

We then used this value along with the total visual magnitude of the system; i.e., $m_{\mathrm{v}} = 8.34$ (esa 1997), in the following equations to get the apparent magnitudes for

[1] The Fourth Catalog of Interferometric Measurements of Binary Stars can be downloaded at *http://www.astro.gsu.edu/wds/int4/int4_20.html*

the two main components of the system; i.e., components A and B

$$m_v^A = m_v + 2.5 \log \left(1 + 10^{-0.4\Delta m}\right) \quad (1)$$

$$m_v^B = m_v^A + \Delta m \quad (2)$$

$$M_V = m_v + 5 - 5 \log d - A_V \quad (3)$$

where the interstellar extinction $A_V = 0.0128$ is calculated utilizing $E(B - V) = 0.004$ (lallement et al. 2018). We used the apparent individual magnitude values calculated from these equations, along with $T_{\rm eff}$, mass, $S_{\rm p}$ and bolometric correction information obtained from Gray (2005) and Lang (1992), to compute the bolometric magnitude $M_{\rm bol}$, R, log g and L of the two main components employing the well-known equations for a main sequence star

$$M_{\rm bol} = M_{\rm bol}^{\odot} - 2.5 \log \left(\frac{L}{L_{\odot}}\right) \quad (4)$$

$$\log \left(\frac{R}{R_{\odot}}\right) = 0.5 \log \left(\frac{L}{L_{\odot}}\right) - 2 \log \left(\frac{T_{\rm eff}}{T_{{\rm eff}_{\odot}}}\right) \quad (5)$$

$$\log g = \log \left(\frac{\rm M}{\rm M_{\odot}}\right) - 2 \log \left(\frac{R}{R_{\odot}}\right) + 4.43 \quad (6)$$

Next, we regarded these estimated values as preliminary input parameters for the grids of Kurucz's line-blanketed plane-parallel models (ATLAS9) to obtain preliminary synthetic SEDs for stars A and B. These were then combined to get the total synthetic SED of the system according to the following equation (Al-Wardat 2012)

$$F_\lambda \cdot d^2 = H_\lambda^A \cdot R_A^2 + H_\lambda^B \cdot R_B^2 \quad (7)$$

which can be written as

$$F_\lambda = (R_A/d)^2 (H_\lambda^A + H_\lambda^B (R_A/R_B)^2) \quad (8)$$

where H_λ^A and H_λ^B represent the flux from a unit surface of the system's components A and B, respectively, and F_λ signifies the total SED of the entire system.

In order to get the best synthetic SED that will give the most accurate physical properties for the system, we need to perform the above steps in an iterative manner using different sets of preliminary input parameters. This should be performed until we obtain synthetic magnitude and color index values that are consistent with those derived from observations (SIMBAD catalog) within the error values.

The synthetic magnitudes can be calculated from the synthetic SED utilizing the following relationship (Al-Wardat 2002, 2008, 2012 and references therein)

$$m_p = -2.5 \log \frac{\int P_p(\lambda) F_{\lambda,s}(\lambda) \lambda d\lambda}{\int P_p(\lambda) F_{\lambda,r}(\lambda) \lambda d\lambda} + ZP_p \quad (9)$$

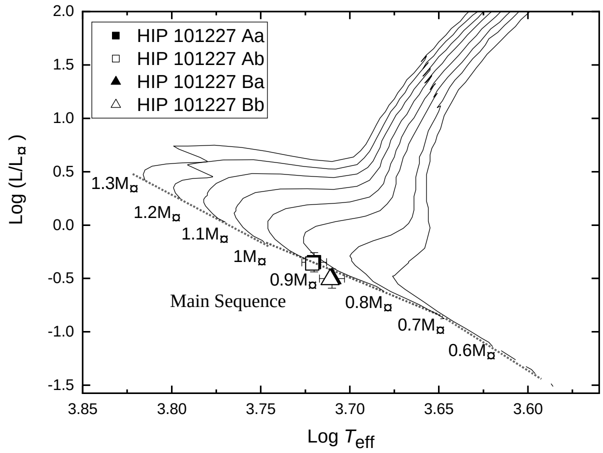

Fig. 1 The positions of each star in the HIP 101227 system on the evolutionary tracks derived by Girardi et al. (2000) assuming that it is a quadruple.

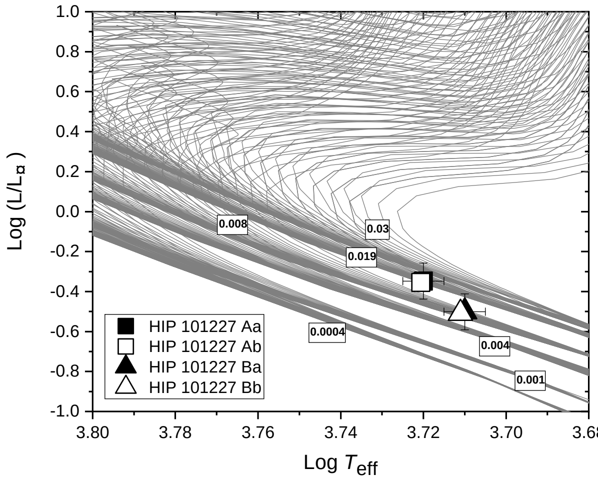

Fig. 2 The positions of each star in the HIP 101227 system on the isochrones for low and intermediate-mass stars with different metallicities derived by Girardi et al. (2000) assuming that it is a quadruple.

where m_p represents the synthetic magnitude of the passband p, P_p is the dimensionless sensitivity function of the pass-band p, and $F_{\lambda,s}(\lambda)$ and $F_{\lambda,r}(\lambda)$ are the synthetic SEDs of the star being studied and the reference star (Vega in this case), respectively. The zero points, Z, were taken from Maíz Apellániz (2007).

2.2 Orbital Analysis

The orbital properties of HIP 101227 were determined following the dynamical modeling technique developed by Tokovinin (2016) (the original paper is Tokovinin (1992)). This method uses the least-squares fits with weights inversely proportional to the observational errors to give the final orbital parameters with their errors by relying on the IDL code ORBIT (Tokovinin 2016)[2]. We utilized relative position measurements from speckle interferometric observations to determine the period (P), epoch of passage through periastron ($T_{\rm o}$), eccentricity (e), semi-major axis (a), inclination (i), longitude of the periastron (ω) and the position angle of the line of nodes (Ω) for the orbit of the two main components of the system.

The code requires the preliminary values of P, $T_{\rm o}$, e, a, i, ω, Ω, the positional measurements and radial velocities of the system. We obtained positional measurements for the system from the Fourth Catalog of Interferometric Measurements of Binary Stars[1] and Mason et al. (2018). The latest measurements, which were not available when Docobo & Ling (2006) did their orbital analysis of the system, are listed in Table 3. We obtained the radial velocities of the whole system from Tabernero et al. (2012) and Gontcharov (2006); i.e., $-23.5 \pm 0.04\,{\rm km\ s^{-1}}$ and $-25.6 \pm 0.90\,{\rm km\ s^{-1}}$, respectively. The radial velocities for the main components of the system, A and B, were referenced from Frasca et al. (2018); i.e., $-31.25 \pm 0.15\,{\rm km\ s^{-1}}$ and $-16.88 \pm 0.15\,{\rm km\ s^{-1}}$, respectively. We input these values in the ORBIT code to determine the best-fit orbit for the system.

3 RESULTS AND DISCUSSION

3.1 Binary, Triple or Quadruple?

Based on the physical properties that were obtained from the best-fit SED of the system as a binary (Table A.1 of the Appendix), we plot the stars on the stellar evolutionary track diagram by Girardi et al. (2000). This is displayed in Figure A.1 (see Appendix). The figure affirms that star A is more evolved than star B even though they have similar masses (mass$_A$ = 0.79 ± 0.20 $M_\odot$ and mass$_B$ = 0.75 ± 0.20 $M_\odot$). We also plot the stars on the metallicity isochrones by Girardi et al. (2000) (Figure A.3 of the Appendix). Based on the figure, we found that both stars deviate significantly from the isochrone tracks. These results provide evidence that HIP 101227 is likely not a binary system.

Therefore, we proceeded with our analysis by assuming that the system is now a triple system as suggested by Tokovinin (2018) and Dommanget & Nys (2002). Based on our analysis of the system as a binary, we found that star A has a larger radius than star B, thus it has a higher probability of consisting of two stars. Hence, we further analyzed star A as a sub-binary system consisting of stars $A_{\rm a}$ and $A_{\rm b}$, assuming that they have very similar properties (i.e., $\Delta m = 0$). The synthetic SED for star A represents the total SED for both stars. We repeated our analysis as described earlier in order to build the individual SEDs for the three stellar components, and measure their physical properties.

We then used the results that we obtained (Table A.2 of the Appendix) to plot the stars on the stellar evolutionary and metallicity isochrone diagrams (Fig. A.2 and A.4 of the Appendix, respectively) by Girardi et al. (2000). Based on Figure A.4, it can be seen that star B is located away from the isochrone tracks. The positions of the stars in the stellar evolutionary diagram are also not consistent with those expected (stars $A_{\rm a}$ and $A_{\rm b}$ are more evolved than star B even though they have similar masses; Mass$_{A_a}$ = Mass$_{A_b}$ = 0.90 ± 0.20 $M_\odot$ and Mass$_B$ = 0.75 ± 0.20 $M_\odot$). Repeating the same analysis by instead assuming that star A is a single star, and star B is a sub-binary system, we obtained similar results (Table A.3 of the Appendix). These indicate that HIP 101227 is likely not a triple stellar system as well, as suggested by Tokovinin (2018) and Dommanget & Nys (2002).

Next, we proceeded by assuming that the system is a quadruple consisting of stars $A_{\rm a}$, $A_{\rm b}$, $B_{\rm a}$ and $B_{\rm b}$. Based on our results, we found that the stars fit very well with the metallicity isochrone tracks shown in Figure 2. The properties of the stars are also consistent with the stellar evolutionary tracks depicted in Figure 1. We therefore conclude that HIP 101227 is a quadruple stellar system consisting of stars $A_{\rm a}$, $A_{\rm b}$, $B_{\rm a}$ and $B_{\rm b}$. In Table 4, we present the physical properties of the system as measured from the best-fit SED of the system. The synthetic magnitudes and color indices determined from the best-fit SED are tabulated in Table 5, in comparison with the observed values obtained from the SIMBAD catalog. As can be seen from the table, the synthetic values that we obtained are highly consistent with those measured from observations. We note that there are no significant differences between the total synthetic SEDs that we obtained when assuming that the system is a binary, triple or quadruple system.

Figure 2 indicates that stars $A_{\rm a}$ and $A_{\rm b}$ have metallicity Z = 0.019 while star $B_{\rm a}$ and $B_{\rm b}$ have Z = 0.008. The total mass of the system is 3.42±0.20 $M_\odot$. This is distributed almost equally between the four stars. Based on the temperatures of the stars, they can be classified as type K0 stars. The very similar physical characteristics of the stars in the system, as presented in Table 4, suggest that the fragmentation process is the most probable theory for the formation of the system as opposed to capture theory. The latter would usually form a system with relatively different properties; e.g., the masses of the stars would be significantly different. Hierarchical fragmentation during rotational collapse has been suggested to produce binaries and multiple systems (Zinnecker 2001). This mechanism

[2] The IDL code ORBIT can be downloaded at *http://www.ctio.noao.edu/{$\sim$}atokovin/orbit/*

Table 3 The latest relative positional measurements for the HIP 101227 system (that was not included in Docobo & Ling 2006) taken from the Fourth Catalog of Interferometric Measurements of Binary Stars. For all positional measurements, please refer to the catalog.

Epoch	Theta ($\theta°$)	Rho (ρ)	λ (nm)	Telescope aperture (m)	Reference
2001.7635	139.4	0.096	541	3.5	Horch et al. (2008b)
2002.7986	153.8	0.080	600	6.0	Balega et al. (2013)
2005.5184	60.9	0.085	520	3.5	Docobo et al. (2008)
2006.5223	75.5	0.099	754	3.5	Horch et al. (2008b)
2006.5223	79.1	0.112	754	3.5	Horch et al. (2008b)
2007.6018	266.0	0.144	550	4.0	Mason et al. (2018)
2007.8197	89.9	0.149	550	3.5	Horch et al. (2010)
2008.4563	273.4	0.166	550	4.0	Mason et al. (2018)
2008.546	97.4	0.203	530	0.7	Gili & Prieur (2012)

is possible if the spinning disk around an incipient central protostar is fragmented, as long as it continues to infall (Bonnell & Bate 1994).

Table 4 Physical Properties of Each Star in the HIP 101227 Quadruple System

Parameters	Comp. $A_{\rm a}$	Comp. $A_{\rm b}$	Comp. $B_{\rm a}$	Comp. $B_{\rm b}$
$T_{\rm eff}$ (K)	5250 ± 30	5250 ± 30	5170 ± 20	5170 ± 20
R ($R_\odot$)	0.81 ± 0.02	0.81 ± 0.02	0.70 ± 0.01	0.70 ± 0.01
Log g	4.60 ± 0.05	4.60 ± 0.05	4.60 ± 0.05	4.60 ± 0.05
L ($L_\odot$)	0.45 ± 0.05	0.45 ± 0.05	0.31 ± 0.05	0.31 ± 0.05
Mass ($M_\odot$)	0.90 ± 0.20	0.90 ± 0.20	0.81 ± 0.20	0.81 ± 0.20

Table 5 Comparison between the total magnitudes determined from the best-fit synthetic SED and those obtained from observations (SIMBAD catalog).

System	Filter	SIMBAD database	This work
Johnson-Cousins	B	9.22	9.22 ± 1.19
	V	8.34	8.34 ± 1.08
	B-V	0.88	0.88 ± 0.11
Tycho	B_T	9.45	9.46 ± 1.23
	V_T	8.44	8.43 ± 1.09
	$B_T - V_T$	1.01	1.01 ± 0.13
Δm	$\cdots$	0.39	0.39 ± 0.05

We can estimate the age of the quadruple system from the isochrone diagram in Figure 2 as follows

$$t_{\rm ms} = f_{\rm ASITR}(m_{A,B} - 5 \log d + 5 - A, Z) \tag{10}$$

where $f_{\rm ASITR}$ is the age-synthetic isochrone track function and Z is the metallicity of the star. Based on this, we found that the age of the system is less than 200 Myr, which means that the four stars are hierarchical zero age main sequence stars (at the last stage of the pre-main sequence). This can also be clearly seen from the positions of the stars on the stellar evolutionary diagram in Figure 1.

3.1.1 Comparison of the best-fit synthetic SED with observational SED

In order to test the reliability of our results, which rely on one of the techniques of Al-Wardat's method, we compare the best-fit total synthetic SED that we determined for the system with its observational SEDs that we obtained specifically for this work, and those firstly obtained by Al-Wardat (2002).

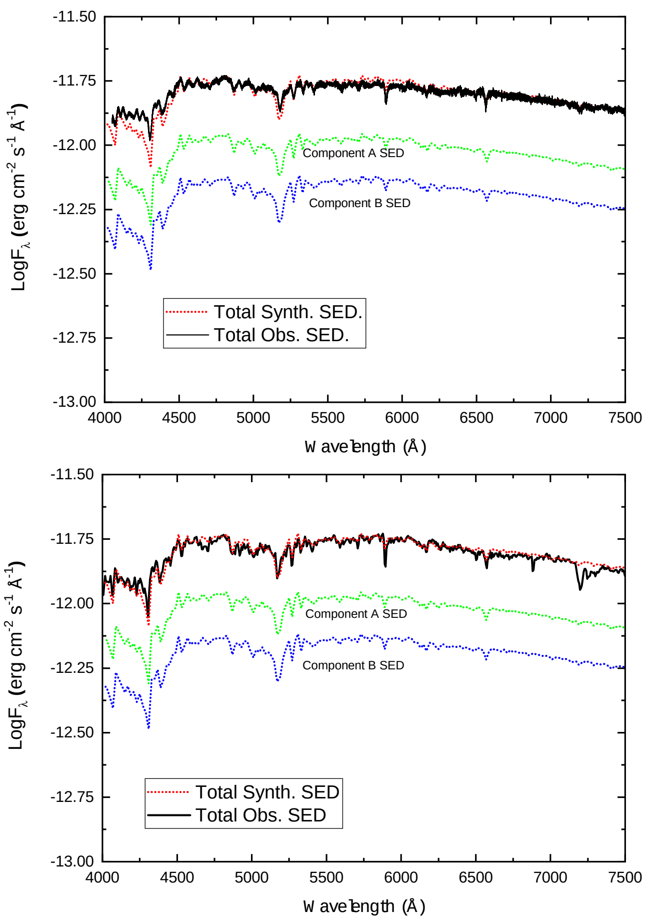

Fig. 3 The best-fit synthetic SEDs for the main stellar components A and B, and the total HIP 101227 system (*dotted lines*) from our work, in comparison with its total SED obtained from our new observations (*solid lines*) at Sharjah Observatory (*top*) and Al-Wardat (2002) (*bottom*).

We acquired a new observational SED for the system at optical wavelengths from the Sharjah Observatory located at Sharjah Academy for Astronomy and Space

Table 6 Orbital parameters of HIP 101227 as measured from our analysis in comparison with those obtained by Docobo & Ling (2006).

Parameter	This work	Docobo & Ling (2006)
P (yr.)	20.514 ± 0.092	33.13
T_o (yr.)	1999.097 ± 0.178	1974.57
e	0.5193 ± 0.0138	0.19
a (arcsec)	0.1989 ± 0.0038	0.213
i (deg)	75.46 ± 0.75	71.5
Ω (deg)	115.9 ± 0.72	25
ω (deg)	307.07 ± 2.20	109.9
$\mathrm{Mass_{Tot}}$ $(M_\odot)$	2.18 ± 0.33	1.03

Sciences in the United Arab Emirates on Julian date 2457201.38422 (one night). A Basic Echelle Spectrograph (BACHES) was utilized with the SBIG ST-8300 camera at the Plane Wave Corrected Dall-Kirkham (CDK) 17-inch reflector telescope.[3] Around 10 spectra were obtained with different exposure times (between 100 s and 300 s). The telescope has a Broad-Band Anti-Reflection (BBAR) multicoated 17" (431.8 mm) aperture, and a focal length of 2939 mm (f/6.8) with a carbon fiber truss design to minimize focus shift with a collimator focal ratio of f/10. The BACHES spectrograph has a spectral range of 392 nm to 800 nm. A 50 µm slit was used, which gives an average spectral resolving power ($R = \lambda/\Delta\lambda$) of 10 000. A thorium-argon cathode and halogen lamp with blue filter were utilized for calibration and flat-field, respectively. Vega was adopted as a reference star.

We stacked the spectra together, and the resultant observational SED for the system is featured in Figure 3. This is compared with the best-fit synthetic SED that we obtained earlier. We also do the same comparison with the old observational SED obtained from Al-Wardat (2002) in Figure 3. Based on this figure, we can see that the best-fit synthetic SED profiles and continuum that we built for the entire HIP 101227 system are generally consistent with both observational SEDs. There is some disagreement between ~4000-4300 Å in our observation. This can be explained by the difference in the CCD's sensitivity between the red and blue parts of the spectrum. Overall however, these results provide further support for the results that we obtained from our analysis, and the reliability of the Al-Wardat (2002) method in determining the physical properties of CVBMSs.

3.2 Orbital Properties

We initially obtained large errors from our orbital modeling of the system by relying on the Tokovinin (2016) method. This is due to the two points from Ismailov (1992) and Hartkopf et al. (2000) which deviate significantly from the other orbital points. We therefore assigned less weight for the two points in our fit, and managed to get the best-fit solution.

[3] Further details on BACHES can be found at *https://academic.oup.com/mnras/article/443/1/158/1481885*

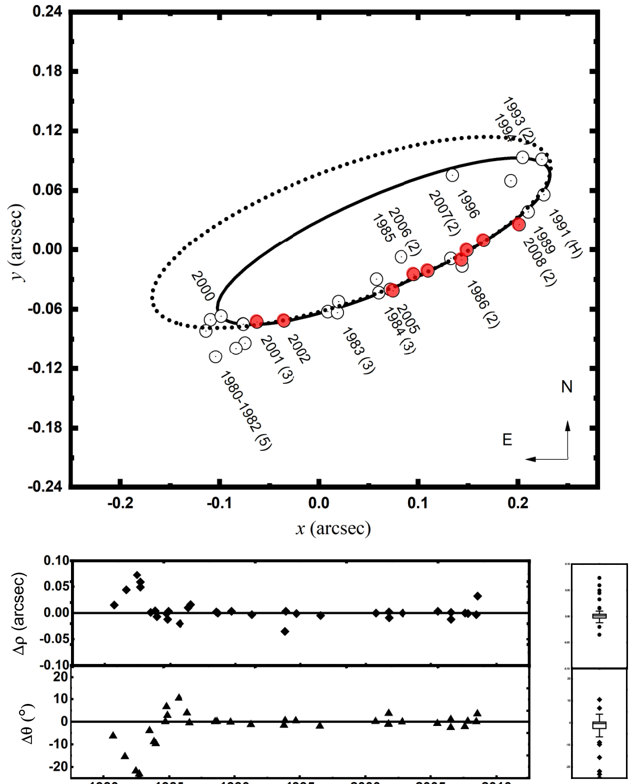

Fig. 4 Orbital solution for the HIP 101227 system as determined from our analysis (*solid line*) and Docobo & Ling (2006) (*dotted line*). The white and red circles are the old and new positional points (listed in Table 3), respectively. The bottom left panel features the fit residuals, showing the difference between the observed and model values for the angular separation ($\Delta\rho$) and position angle ($\Delta\theta$) of the orbit. The bottom right panel represents the distribution of data based on a five-number summary ("minimum," first quartile (Q1); median, third quartile (Q3); and "maximum") and outliers.

We plot our orbital solution in Figure 4, in comparison with that obtained by Docobo & Ling (2006). Based on this figure, it can be seen that the two orbits are significantly different from each other, and our orbit fits the observed positional measurements better than Docobo & Ling (2006). The average residuals for the fit are -2.77° and 6.26 mas for θ and ρ, respectively, and the root-mean-square (RMS) values are 7.8833° and 0.02172 mas for θ and ρ, respectively. We tabulate the orbital properties of the system that we obtained from our analysis in Table 6.

We can independently calculate the total mass of the system using the orbital properties that we obtained from this dynamical analysis. This can be determined via

Kepler's third law, which is given by

$$\begin{aligned} \mathrm{Mass_{Tot}} &= \frac{(\mathrm{Mass_{A_a}} + \mathrm{Mass_{A_b}} + \mathrm{Mass_{B_a}} + \mathrm{Mass_{B_b}})}{M_\odot} \\ &= (a^3/\pi^3 P^2) \end{aligned} \tag{11}$$

where the unit of P is in years, and a and π are in arcseconds. Based on Equation (11), we calculated a total dynamical mass of 2.18 ± 0.33 $M_\odot$ for the system. This value is significantly smaller than the total mass determined from our SED analysis; i.e., 3.42 ± 0.20 $M_\odot$. A reason for this could be due to inaccuracy in the parallax measurement. The same mass can be obtained if the parallax of the system was to be ≈17.95 mas.

We note that in a private communication with J. A. Docobo during the final submission stage of this paper, we were informed that in their work (Docobo and Campo in preparation), they performed orbital modeling for this system using the same data points as ours, with a different method. The results that they obtained are as follows: P = 20.414 yr, T_o = 1999.240 yr, e = 0.5238, a = 0.2011 arcsec, i = 76.03°, Ω = 116.69° and ω = 307.21°, with RMS of 7.636° and 0.0221 mas for θ and ρ respectively. These orbital elements are highly consistent with those determined in our work (Table 6), providing further support for the results that we obtained.

4 CONCLUSIONS

In this paper, we analyzed the stellar system HIP 101227 to determine the total number of components in the system, and their properties. We used recent data and methods developed by Al-Wardat (2002) (atmospheric modeling) and Tokovinin (2016) (dynamical modeling) to determine the physical properties and orbital solution for the system, respectively, with better accuracy than past studies. Based on our analysis, we found that the system is more consistent with being a quadruple rather than a binary, or a triple system as suggested by previous studies. This hierarchical quadruple system consists of four zero-age main sequence stars (at the last stage of the pre-main sequence), with age less than 200 Myr and very similar physical properties. Due to their very similar characteristics, we suggested that the fragmentation process is the most probable mechanism for the formation of the system.

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Appendix A: RESULTS FOR BINARY AND TRIPLE SYSTEM ANALYSIS

Here we provide the results of our analysis when assuming that the system is a binary and triple system, which was discussed in Section 3.1. This includes the physical properties that we determined (Table A.1-A.3), as well as the associated evolutionary track and isochrone diagrams (Figs. A.1-A.2 and Figs. A.3-A.4, respectively).

Table A.1 Physical properties of each star in HIP 101227 when assuming that it is a binary system.

Parameters	Comp. A	Comp. B
T_eff (K)	5250 ± 30	5170 ± 20
$R\,(R_\odot)$	1.14 ± 0.01	1.00 ± 0.01
Log g	4.60 ± 0.05	4.60 ± 0.05
$L\,(L_\odot)$	0.89 ± 0.11	0.64 ± 0.08
Mass ($M_\odot$)	0.79 ± 0.20	0.75 ± 0.20

Table A.2 Physical properties of each star in HIP 101227 when assuming that it is a triple system, with component A being a sub-binary.

Parameters	Comp. A_a	Comp. A_b	Comp. B
T_eff (K)	5250 ± 30	5250 ± 30	5170 ± 20
$R\,(R_\odot)$	0.81 ± 0.02	0.81 ± 0.02	1.00 ± 0.01
Log g	4.60 ± 0.05	4.60 ± 0.05	4.60 ± 0.05
$L\,(L_\odot)$	0.45 ± 0.05	0.45 ± 0.05	0.64 ± 0.08
Mass ($M_\odot$)	0.90 ± 0.20	0.90 ± 0.20	0.75 ± 0.20

Table A.3 Physical properties of each star in HIP 101227 when assuming that it is a triple system, with component B being a sub-binary.

Parameters	Comp. A	Comp. B_a	Comp. B_b
T_eff (K)	5250 ± 30	5170 ± 20	5170 ± 20
$R\,(R_\odot)$	1.14 ± 0.01	0.70 ± 0.01	0.70 ± 0.01
Log g	4.60 ± 0.05	4.60 ± 0.05	4.60 ± 0.05
$L\,(L_\odot)$	0.89 ± 0.11	0.31 ± 0.05	0.31 ± 0.05
Mass ($M_\odot$)	0.79 ± 0.20	0.81 ± 0.20	0.81 ± 0.20

References

Al-Wardat, M. A. 2002, Bulletin of the Special Astrophysics Observatory, 53, 51

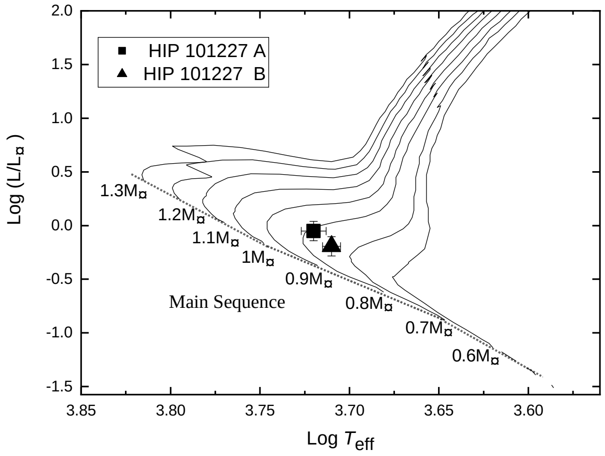

Fig. A.1 The positions of each star in the HIP 101227 system on the evolutionary tracks derived by Girardi et al. (2000) assuming that it is a binary.

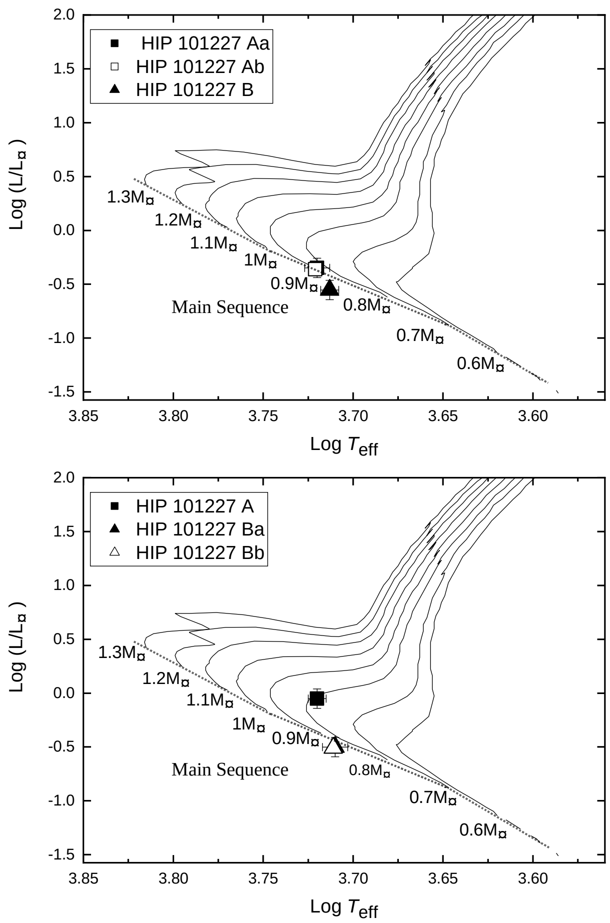

Fig. A.2 The positions of each star in the HIP 101227 system on the evolutionary tracks derived by Girardi et al. (2000) assuming that it is a triple in A (*top*) and triple in B (*bottom*).

Al-Wardat, M. A. 2007, Astronomische Nachrichten, 328, 63
Al-Wardat, M. A. 2008, Astrophysical Bulletin, 63, 361
Al-Wardat, M. A. 2009, Astronomische Nachrichten, 330, 385

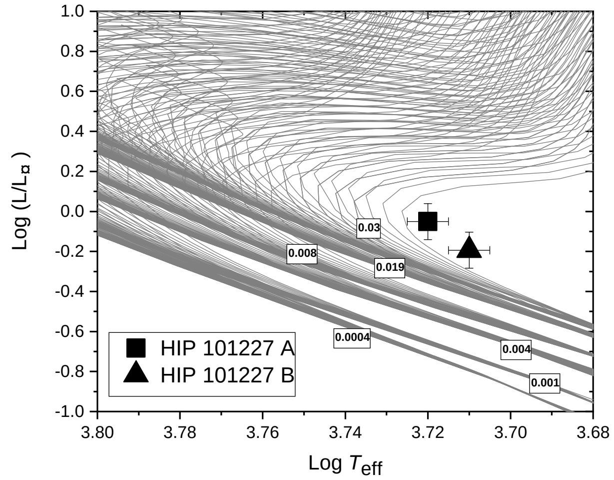

Fig. A.3 The positions of each star in the HIP 101227 system on the isochrones for low and intermediate-mass stars with different metallicities derived by Girardi et al. (2000) assuming that it is a binary.

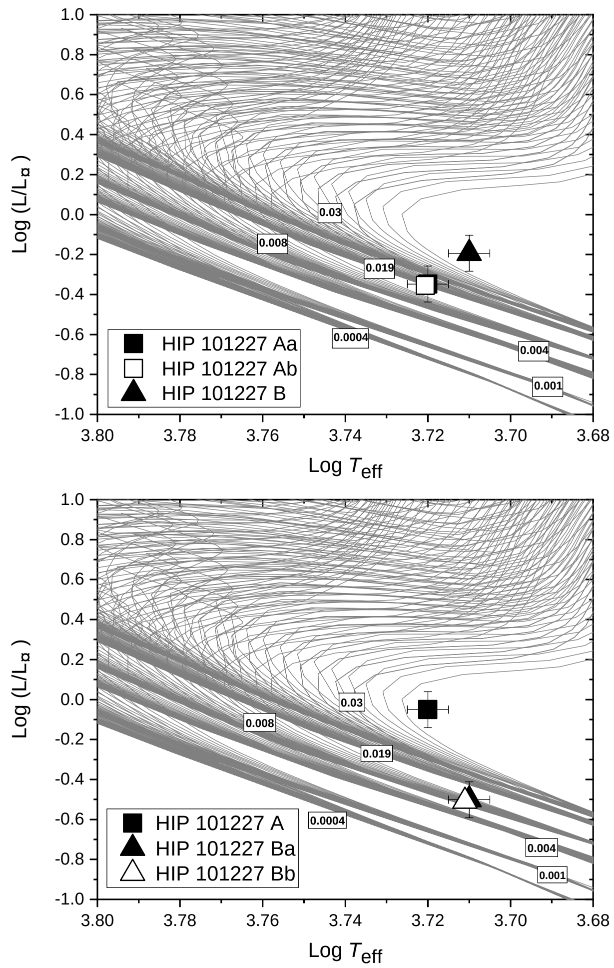

Fig. A.4 The positions of each star in the HIP 101227 system on the isochrones for low and intermediate-mass stars with different metallicities derived by Girardi et al. (2000) assuming that it is a triple in A (*top*) and triple in B (*bottom*).

Al-Wardat, M. 2012, PASA, 29, 523
Al-Wardat, M. A., Balega, Y. Y., Leushin, V. V., et al. 2014a, Astrophysical Bulletin, 69, 58
Al-Wardat, M. A., Balega, Y. Y., Leushin, V. V., et al. 2014b, Astrophysical Bulletin, 69, 198
Al-Wardat, M. A., El-Mahameed, M. H., Yusuf, N. A., Khasawneh, A. M., & Masda, S. G. 2016, RAA (Research in Astronomy and Astrophysics), 16, 166
Al-Wardat, M. A., Docobo, J. A., Abushattal, A. A., & Campo, P. P. 2017, Astrophysical Bulletin, 72, 24
Al-Wardat, M. A., & Widyan, H. 2009, Astrophysical Bulletin, 64, 365
Balega, I. I., Balega, Y. Y., Maksimov, A. F., et al. 2006, Bulletin of the Special Astrophysics Observatory, 59, 20
Balega, I. I., Balega, Y. Y., Gasanova, L. T., et al. 2013, Astrophysical Bulletin, 68, 53
Balega, Y. Y., & Tikhonov, N. A. 1977, Soviet Astronomy Letters, 3, 272
Bonnell, I. A., & Bate, M. R. 1994, MNRAS, 269, L45
Borkovits, T., Hajdu, T., Sztakovics, J., et al. 2016, MNRAS, 455, 4136
Borkovits, T., Rappaport, S., Kaye, T., et al. 2019, MNRAS, 483, 1934
Docobo, J. A., & Ling, J. F. 2006, IAU Commission on Double Stars, 160, 2
Docobo, J. A., Tamazian, V. S., Andrade, M., et al. 2008, AJ, 135, 1803
Dommanget, J., & Nys, O. 2002, VizieR Online Data Catalog, I/269A
Duquennoy, A., & Mayor, M. 1992, Binaries as Tracers of Stellar Formation (Cambridge Univ. Press)
ESA Special Publication 1997, ESA Special Publication, 1200, The HIPPARCOS and TYCHO Catalogues. Astrometric and Photometric Star Catalogues Derived from the ESA HIPPARCOS Space Astrometry Mission
Frasca, A., Guillout, P., Klutsch, A., et al. 2018, A&A, 612, A96
Gili, R., & Prieur, J. L. 2012, Astronomische Nachrichten, 333, 727
Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, A&AS, 141, 371
Gontcharov, G. A. 2006, Astronomy Letters, 32, 759
Gray, D. F. 2005, The Observation and Analysis of Stellar Photospheres (Cambridge Univ. Press)
Hartkopf, W. I., Mason, B. D., McAlister, H. A., et al. 2000, AJ, 119, 3084
Hilditch, R. W. 2001, An Introduction to Close Binary Stars (Cambridge Univ. Press)
Høg, E., Fabricius, C., Makarov, V. V., et al. 2000, A&A, 355, L27
Horch, E. P., Falta, D., Anderson, L. M., et al. 2010, AJ, 139, 205
Horch, E. P., Meyer, R. D., & van Altena, W. F. 2004, AJ, 127, 1727
Horch, E. P., van Altena, W. F., Cyr, William M., J., et al. 2008a, AJ, 136, 312
Horch, E. P., van Altena, W. F., Cyr, William M., J., et al. 2008b, AJ, 136, 312
Ismailov, R. M. 1992, A&AS, 96, 375
Koçak, D., İçli, T., & Yakut, K. 2020, Contributions of the Astronomical Observatory Skalnate Pleso, 50, 508
Labeyrie, A. 1970, A&A, 6, 85
Lang, K. R. 1992, Astrophysical Data I. Planets and Stars (Springer-Verlag Berlin Heidelberg New York)
Lallement, R., Capitanio, L., Ruiz-Dern, L., et al. 2018, A&A, 616, A132
Maíz Apellániz, J. 2007, in Astronomical Society of the Pacific Conference Series, 364, ed. C. Sterken, 227
Malkov, O. Y., Tamazian, V. S., Docobo, J. A., & Chulkov, D. A. 2012, A&A, 546, A69
Masda, S. G., Al-Wardat, M. A., Neuhäuser, R., & Al-Naimiy, H. M. 2016, RAA (Research in Astronomy and Astrophysics), 16, 112
Masda, S. G., Al-Wardat, M. A., & Pathan, J. K. M. K. 2018, RAA (Research in Astronomy and Astrophysics), 18, 072
Masda, S. G., Al-Wardat, M. A., & Pathan, J. M. 2019a, RAA (Research in Astronomy and Astrophysics), 19, 105
Masda, S. G., Docobo, J. A., Hussein, A. M., et al. 2019b, Astrophysical Bulletin, 74, 464
Mason, B. D., Hartkopf, W. I., Miles, K. N., et al. 2018, AJ, 155, 215
Schlafly, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103
Sürgit, D., Erdem, A., Engelbrecht, C. A., & Marang, F. 2020, MNRAS, 493, 2659
Tabernero, H. M., Montes, D., & Gonzalez Hernandez, J. I. 2012, VizieR Online Data Catalog, J/A+A/547/A13
Tokovinin, A. 1992, in Astronomical Society of the Pacific Conference Series, 32, IAU Colloq. 135, eds. H. A. McAlister, & W. I. Hartkopf, 573
Tokovinin, A. 2016, AJ, 152, 11
Tokovinin, A. 2018, ApJS, 235, 6
van Leeuwen, F. 2007, A&A, 474, 653
Zinnecker, H. 2001, in The Formation of Binary Stars, eds. H. Zinnecker, & R. Mathieu, 200, 1