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The Precise Individual Masses and Theoretical Stability and Habitability of some Single-lined Spectroscopic Binaries

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Abstract

Over the past few decades, some Spectroscopic Binaries (SBs) have been resolved using high-resolution techniques. Astrophysics is interested in this subject because we can obtain the mass of each component. By combining a visual solution with a complimentary one, such as the spectroscopic orbit or Edward method, we can determine the individual masses, semimajor axes, magnitudes, spectral types, radii, and temperatures. These provide the most probable physical parameters for some single-lined spectroscopic binaries. Then We can use these parameters to calculate theoretical the stability and habitability of the system. Additionally, we assume the composite spectrum, the apparent global magnitude, and the parallax (generally the Hipparcos, and recently the Gaia). The next step is to obtain the spectrum for each components. The Edwards method will be used in this case. As soon as we have two spectra foe two single-lined spectroscopic binaries (HIP 754 and HIP 3841), we can determine each mass based on the magnitude difference, Δm. For selected samples, we calculate the rest of the physical parameters needed to calculate the theoretical stability and habitability.

Keywords: *binaries, visual, single-lined spectroscopic, stars, physical parameters, stability, habitability*

1. Introduction

Binary systems exhibit periodic oscillations in radial velocity due to their orbital motion. These oscillations are evident in the Doppler shifts of spectral lines. A single-lined spectroscopic binary star has only one set of lines. The peculiar characteristics of their velocity and light curves exclude these from being categorized as single-lined spectroscopic binaries, even though many intrinsic variable stars have cyclic variations in radial velocity. We recognize most stars to be double stars today as single-lined spectroscopic binaries, though a few single stars with unusual characteristics may also qualify. Spectroscopic observations of double stars enable us to study their orbital motions. A BS is an ideal environment for searching for exoplanets. Astrometric, spectroscopic, and eclipsing binary systems are the three main types. Mass determination is a difficult technique. (Al-Wardat et al., 2017, Duquennoy & Mayor, 1991, Raghavan et al., 2010). A stellar mass can be determined from the orbits and parallaxes of binaries and multiple stars, which is one of the reasons why astronomy and astrodynamics are interested in them. The mass of stars affects studies of their evolution fundamentally. Also available are luminosity, parallaxes, sizes, and orbital elements, which can be used to evaluate parameters of interests, and orbital elements.(Al-Tawalbeh et al., 2021, Docobo et al., 2018, Hussein et al., 2022).

The search for stars that are in the main sequence and premain sequence is a method used by missions such as CoRoT, Kepler, and K2 to find exoplanets. In the past 50 years, speckle interferometry has been used by researchers around the world to observe binary stars effectively and accurately. Astrometric parallaxes for bright stars found systematic errors in Gaia, so both types of parallaxes were regarded as effective verification methods. Physical parameters have been determined with this research method in many publications over the years (Abushattal, 2017, Abushattal et al., 2019a, Docobo et al., 2017, Masda et al., 2016).

High resolution techniques have been used to resolve a number of spectroscopic binaries. However, before choosing a particular telescope to resolve SBs, we should consider the following questions. We would like to know how big a telescope we would need for each case. We would like to know what size telescope we would need. In order to prepare a telescope list, what is the best way to do it? The purpose of this paper is to

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answer these questions by considering SBs with known orbits and parallaxes. We propose the maximum and minimum angular separations between these SBs using a three-dimensional model. Furthermore to describe the habitability and stability around single-lined spectroscopic binaries. A description of these systems is provided along with their spectral spectra, magnitudes, and masses. Spectroscopic orbits, composite spectra, and apparent magnitudes of each component can be used to calculate a visual orbit. Find the critical distances between the components by drawing the apparent orbit and calculating the critical angular distances. Additionally, we examine other optically resolvable systems and determine telescope sizes.

Many physical processes can be observed in a binary system, including mass loss, mass exchange, component variability, the Nova phenomenon, the Flare phenomenon, and X-ray binaries. Among the different aspects of the dynamical approach are perturbations, the discovery of dark components, such as brown stars and exoplanets, as well as orbit calculation (Abushattal et al., 2019b, Taani et al., 2019a,b, 2020). CoRoT, Kepler, and TESS are all capable of finding Earth-like planets within BSs, which occur in half of multiple stars. As multiple stars form, they often host the most massive exoplanets. Binary star systems are also powerful hosts of many exoplanets, due to the stages of star formation. Binary stars' properties determine their habitability and stability. A major objective of this work is to determine each planet's mass, semi-major axis, luminosities, and temperatures, which are the most important parameters.

2. Single-lined spectroscopic binaries

The following orbital parameters are known for a SB1 binary with an orbit: P (periastron period), T (periastron epoch), e (eccentricity), $A_1 = a_1.\sin(i)$ (a_1 represents the semimajor axis of the main component's orbit, and i indicates its inclination), Ω (periastron argument for the main component's orbit), and the mass function.

$$f(\mathcal{M}) = \frac{(\mathcal{M}_2.sin(i))^3}{(\mathcal{M}_1 + \mathcal{M}_2)^2} \tag{1}$$

Additionally, we know the global apparent magnitude, the parallax and the spectrum components (typically the Hipparcos and Gaia parallax). It is first necessary to obtain information on each star's individual spectrum before we can analyze its spectrum. In order to accomplish this, we will use the Edwards method (Abushattal et al., 2019a, Edwards, 1976).

The magnitude difference, Δm, must be used to assign the corresponding masses to each star. This necessitates an analysis of the current calibrations. Knowing the masses of components around the center of mass will allow us to determine the three semimajor axes: a (relative orbit), a_1, and a_2 (these last ones represent the orbits of the components around the center of mass). The semimajor axis of the orbit is a$''$ (in arc seconds) and the orbital inclination is i.

A 'visual binary' already exists in these conditions, except for the node. Two points should be noted, however.

- Due to the fact that we will determine the inclination using $\sin(i)$, there are two possible values for this element: i and i'=180° - i. It is impossible to determine the direction of motion without optical resolution of the binary.

- Furthermore, we are unsure of the angle of the node (Ω), but this poses no problem. It can be taken as zero for our purposes.

Application of the methodology to the SB1, HIP 754 system

Using the Edward method, we will calculate the physical and orbital properties of binary stars based on their spectral type. In Abushattal (2017) the same method is used, but he began by using astrophysical relationships to calculate apparent magnitude and parallax.

As a single-lined spectroscopic binary system, HIP 754 has the following information, which can be found in Table 1: spectral type, global visual magnitude m, Hipparcos parallax (Gaia did not determine HIP 754 parallax), the orbital elements (P, T, e, $a_1.\sin(i)$, ω_1), and the mass function, ($f(\mathcal{M})$).

Due to the fact that HIP 754 is a SB1, Δm is assumed to equal 1.5. Consequently, the lower limit will be $\Delta m = 1.5$ and the upper limit will be $i = 90$. By using the Edwards process, $\Delta m = 1.5$ and S = 0.30. The absolute magnitude will be M_1 = M - 0.30 = 5.97 - 0.30 = 5.67. By means of our calibrations, the absolute apparent magnitude of 5.67 corresponds to the G8V spectral type with a mass of $\mathcal{M}_1 = 0.928 \pm 0.045\mathcal{M}_\odot$.

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Table 1. HIP 754. Physical and orbital parameters

Sp type	K0V
V (mag)	7.77± 0.01
π_{Hip} (mas)	19.45± 1.40
π_{Gaia}(mas)	-
P (days)	463.44 ± 0.18
T $_{(MJD)}$	56108.7 ± 0.9
e	0.293 ± 0.003
$a_1\sin(i)$(Gm)	70.48 ± 0.29
ω_1(degree)	274.7± 0.8
$f(\mathcal{M})(\mathcal{M}_\odot)$	0.0652 ± 0.0008

Regarding the secondary component, its absolute magnitude will be $M_2 = M_1 + 1.5 = 7.17$. This value corresponds to the K4V spectral type with a mass of $\mathcal{M}_2 = 0.720 \pm 0.024\ \mathcal{M}_\odot$.
According to the expressions (3.14) and (3.15), we obtain the following values of the semi-major axes:

$$a = 1.3855 \pm 0.0076_{A.U},$$

$$a_1 = 0.6064 \pm 0.0294_{A.U}, \text{ and}$$

$$a_2 = 0.7791 \pm 0.0569_{A.U},$$

the orbital inclination is,

$$i = 51.1^\circ \pm 2.9^\circ or 128.9^\circ \pm 2.9^\circ.$$

The following Table shows the corresponding results for different initial values of Δm for HIP 754.

Table 2. Orbital inclination and intermediary parameters as a function of Δm

Δm	S	M_1	M_2	Sp_1	Sp_2	$\mathcal{M}_{1(\mathcal{M}_\odot)}$	$\mathcal{M}_{2(\mathcal{M}_\odot)}$	$a_{(A.U)}$	$\sin(i)$	i
1.5	0.27	5.70±0.02	7.70±0.03	G8V	K5V	0.914±0.045	0.677±0.019	1.3683±0.0070	0.810	54.1±3.0
2.0	0.23	5.74±0.02	8.24±0.02	G8V	K7V	0.910±0.044	0.606±0.016	1.3475±0.0067	0.878	61.4±3.2
2.5	0.18	5.79±0.02	8.79±0.02	G9V	K9V	0.901±0.043	0.559±0.020	1.3294±0.0068	0.927	68.0±3.9
3.0	0.14	5.83±0.02	9.33±0.02	G9V	M1V	0.884±0.042	0.500±0.024	1.3061±0.0078	0.999	≅90

When $\sin(i) = 1$, Δm is very close to 3.0. So, the possible scenarios for HIP 754 are between $\Delta m = 1.5$ and $\Delta m = 3.0$.

Now, following the explanations of subsection, we will obtain the maximum and minimum values of ρ'' for different values of Δm (see Table 3).

Table 3. Semimajor axis and the maximum and minimum values of the angular separation, ρ'', as a function of Δm

Δm	a"	ρ''_{max}	ρ''_{min}
1.5	0.0266±0.0019	0.0267±0.0019	0.0081±0.0006
2.0	0.0262±0.0019	0.0261±0.0019	0.0077±0.0005
2.5	0.0259±0.0019	0.0255±0.0018	0.0046±0.0003
3.0	0.0254±0.0018	0.0249±0.0018	0.0014±0.0003

In conclusion, the most probable values of ρ''_{max} are between $0.''0272 \pm 0.0020$ and $0.''0249 \pm 0.0018$. In these conditions, a telescope of 4.30 m (or larger) of diameter will be necessary to try to optically resolve this system in the epochs when ρ'' is near to the maximum value.

3. Stability

An orbital parameters; eccentricity, semimajor axis, and inclination do not change significantly over time is considered stable system. The purpose of this section is to investigate and determine the likely stable

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Table 4. Physical Parameters SB1

Name (HIP)	$\pi_{Hip(mas)}$	$\pi_{Gaia(mas)}$	$m_{(mag)}$	Sp	Sp_1	Sp_2	$\mathcal{M}_1(\mathcal{M}_\odot)$	$\mathcal{M}_2(\mathcal{M}_\odot)$
754	19.45±1.40	-	7.77	K0V	G8V	K4V	0.93±0.05	0.72±0.03
				K0V	G8V	K7V	0.91±0.04	0.61±0.02
				K0V	G9V	M1V	0.88±0.04	0.50±0.02
3841	4.63±1.03	2.55±0.35	8.93	K2III	K4III	A6IV	1.73±0.26	2.09±0.13
				K2III	K2III	G3V	1.79±0.57	1.03±0.04
				K2III	K2III	M1V	1.88±0.40	0.50±0.02

Table 5. Dynamical Parameters For SB1

Name(HIP)	$a_{(AU)}$	$a_{1(AU)}$	$a_{2(AU)}$	$i_{(degree)}$	$\rho_{max(mas)}$	D(m)
754	1.386±0.008	0.606±0.029	0.779±0.057	51.1±2.9	0.0272±0.0020	4.3
3841	2.959±0.027	1.618±0.159	1.341±0.226	9.6±0.9	0.0120±0.0020	10.0

regions of two single-lined spectroscopic systems. Based on the empirical expression of (Holman & Wiegert, 1999), we can determine planetary orbit stability around binary systems. Three types of stable orbits were described by Dovark during the 1980s: The satellite orbits (S-type) involve the planet orbiting around one of the binary's components, The planet-type orbits (P-type) when the planet orbits the binary star around both components. Which is a circumbinary planet, and, The librator-type orbits (L- type) where the stable orbit is around the Lagrangian points (Dvorak, 1984).

Holman - Wiegert empirical expression In 2007, Holman and Wigeret came up with the same equation as Dvorak as a function of mass ratio and semimajor axis. This applies to both S- and P-type orbits (Holman & Wiegert, 1999, Wiegert & Holman, 1997).

In the inner region of the S-type, the expression is:

$$\begin{aligned}\frac{a_s}{a} &= (0.464 \pm 0.006) + (-0.380 \pm 0.010)\mu + (-0.631 \pm 0.034)e \\ &+(0.586 \pm 0.061)\mu e + (0.150 \pm 0.041)e^2 + (-0.198 \pm 0.047)\mu e^2.\end{aligned} \tag{2}$$

The expression for the P- type (the outer region) is:

$$\begin{aligned}\frac{a_i}{a} &= (1.60 \pm 0.04) + (4.12 \pm 0.09)\mu + (5.10 \pm 0.05)e + (-4.27 \pm 0.17)\mu e \\ &+(-2.22 \pm 0.11)e^2 + (-5.09 \pm 0.11)\mu^2 + (4.61 \pm 0.36)\mu^2 e^2.\end{aligned} \tag{3}$$

The stability of each orbit around a star is expressed in terms of two distance values, which are important to understand here:a_{max}(A.U) is the distance around a star at which the orbit of an exoplanet remains stable regardless of the presence of the second component. There is also the second value a_{min}(A.U) which represents the distance closest to the star at which the possibility of stable orbits of exoplanets exists, however a guarantee of stability is not available. We have to take into account the spectral type and the size of the star. This is because, in some cases, the radius of the star is very close to the minimum value for stability. Further, there may be a limit to the maximum stability of the star in some cases.

4. Habitability

During his time at the University of Edinburgh, Cockell provided a useful definition of habitability. An environment that is habitable can support metabolic activities for at least one known organism, enabling it to survive, grow, maintain, or reproduce. (Cockell et al., 2016).

It is necessary for the liquid state of water on an exoplanet in order to support life's basic processes; not cold or hot, and its temperature is determined by many factors, including radio activity and atmospheric

Table 6. Physical parameters for the 17 single-lined spectroscopic binaries

Name (HIP)	e	$a_{(A.U)}$	Δm	$\mathcal{M}_1(\mathcal{M}_\odot)$	$\mathcal{M}_2(\mathcal{M}_\odot)$
754	0.293±0.003	1.385±0.008	1.5	0.93±0.05	0.72±0.026
		1.306±0.008	3.0	0.88±0.04	0.50±0.024
3841	0.562±0.010	2.959±0.027	1.5	1.73±0.26	2.09±0.13
		2.526±0.046	9.0	1.88±0.40	0.50±0.02

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Table 7. The stability limits for exoplanet orbits around each component and both components, in the 17 single-lined spectroscopic binaries

Name (HIP)	$a_{1S_{max}(A.U)}$	$a_{1S_{min}(A.U)}$	$a_{1P_{min}(A.U)}$	$a_{2S_{max}(A.U)}$	$a_{2S_{min}(A.U)}$
754	0.272	0.230	4.306	0.220	0.175
	0.280	0.242	**4.519**	0.198	0.149
3841	0.319	0.090	**9.904**	0.350	0.138
	0.369	0.224	9.6350	0.202	0.029

Table 8. Stellar parameters used to study the habitable zone for the two single-lined spectroscopic binaries

HD	$a_{(A.U)}$	Sp_1	Sp_2	$T_1(K)$	T_2(K)	$L_1(L_\odot)$	L_2 $(L_\odot)$	$\mathcal{M}_1(\mathcal{M}_\odot)$	$\mathcal{M}_2(\mathcal{M}_\odot)$
754	1.386±0.008	G8V	K4V	5486	4798	0.47	0.090	0.93±0.05	0.72±0.03
		G9V	M1V	5384	4144	0.37	0.005	0.88±0.04	0.50±0.02
3841	2.959±0.027	K4III	A6IV	4798	8121	42.07	20.890	1.73±0.26	2.09±0.13
		K2III	M1V	5055	4144	41.69	0.005	1.88±0.40	0.50±0.02

constituents. A parameter's external value depends on where the radiation is coming from depending on its distance from the nearest star. In order to find exoplanets with liquid water, it is first necessary to determine their habitable zones (HZ). The HZ appears as a spherical shell around a single star or a binary star. To determine whether a binary system is habitable, several parameters must be considered: $\mathcal{M}_1(\mathcal{M}_\odot)$, $\mathcal{M}_2(\mathcal{M}_\odot)$, the period (P), the eccentricity (e), and the semimajor axis of the exoplanet's orbit (a)(Mason et al., 2013). As the planet migrates out of the habitable zone due to the tidal force, the semimajor axis and eccentricity can change due to the gravitational force generated by the host star. Because of this, exoplanets are becoming less habitable over time, and habitability is changing (Barnes et al., 2007, Barnes et al., 2008).

In binary systems with fewer than 50 AU between two stars, the gravity of one star perturbs the orbit of an exoplanet and prevents it from containing liquid water (Eggl et al., 2012).

For the purposes of determining a habitable zone for spectroscopic binaries, the following parameters are fixed: temperature derived from the table describing spectral types developed by (Gray, 2005), mass derived from our previous chapter methodology, and luminosity derived from the relation between luminosity and absolute magnitude.

$$\frac{L}{L_\odot} = -\frac{M_v - M_{v\odot} - (BC - BC_\odot)}{2.5}, \tag{4}$$

where, L is the luminosity of the star, M_v is the absolute magnitude ($M_{v\odot}$ = 4.82), and BC is the bolometric correction ($BC_\odot$ = -0.08).

Using Tobias Muller and Nader Haghighipour's 2013 website (http://astro.twam.info/hz/), the habitable zone of single, double, and multiple stars is determined (see (Müller & Haghighipour, 2014). This website includes a habitable zone calculator, tables, plots, and videos that simulate the motion of exoplanets around stars. There are four different models available on this website: (Kasting et al., 1993, Kopparapu, 2013, Kopparapu et al., 2014, Selsis et al., 2007). It the HZ calculator on this website describe the stability using the Holman & Wiegert (1999) model.

As we mentioned before, the habitable zone provides the area around each component or around both components in which the existence of liquid water is possible. We have calculated all parameters which allow us to use a methodology of to describe the habitable zone around the stars of our sample of two single-ined spectroscopic binaries.

Our sample of two spectroscopic binaries allows us to describe the habitable zone around the stars using the methodology of (Müller & Haghighipour, 2014).

5. The Graphics of the Stability and Habitable Zones

As we discussed in the previous sections, stable orbits can be identified within habitable zones by combining stability zones and habitable zones see figure 1, and 2. In case the habitable and stable areas are compatible, there is a possibility of having an exoplanet with liquid water.

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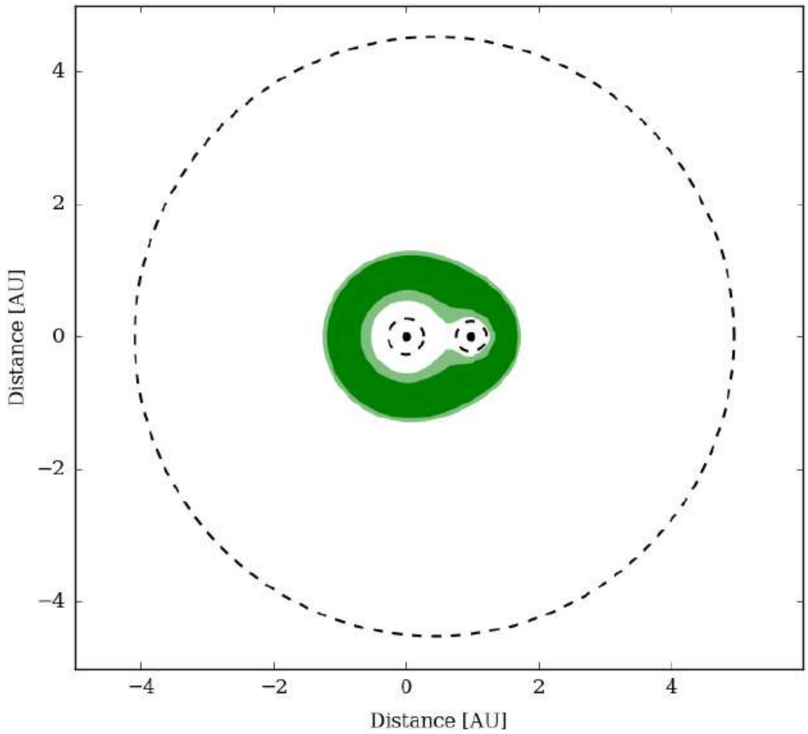

Figure 1. Stability and Habitable Zones for SB1 HIP 754

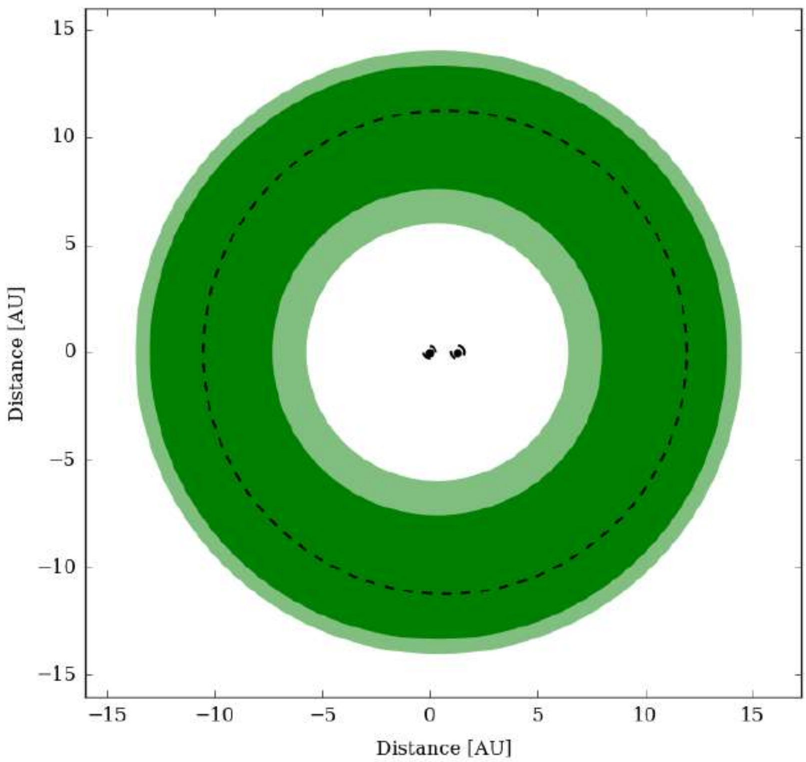

Figure 2. Stability and Habitable Zones for SB1 HIP 3841

6. Conclusions and Future Work

We analyze two binary stars using the Edward method and perform a spectro-interferometric analysis to determine their physical and orbital properties. With the new method, stability, habitability and astronomical parameters such as orbital parallax and mass, as well as semi-major axis have been calculated for two single-lined spectroscopic systems with recent orbital calculation results. In this way, we can determine whether the host system is stable and habitable enough to host an exoplanet or the existance of earth-like planets.

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