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The Physical Parameters, Stability, and Habitability of some Double-lined Spectroscopic Binaries

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Abstract

Large ground telescopes can now resolve most double-lined binaries optically at some point in their orbit due to the improvement of imaging techniques in recent decades. Using additional information about these systems, such as astrometric parallax, even a single precise visual observation can provide a 3D orbit and the primary physical parameters. Furthermore, both the visual and spectroscopic orbits can be determined. We combine the Edward method with the visual solution and the spectroscopic orbit parameters: period (P), periastron epoch (T), eccentricity (e), semimajor axis (a1,2) and inclination (i), we also know the mass ratio of the system. The developed method allows us to select double-lined spectroscopic systems with recently calculated orbits. We calculate the individual masses, orbital parallax, and other fundamental astrophysical parameters. The purpose of these parameters is to verify the reliability of the data received from space missions and to calculate the stability and habitability, which is the primary goal of this study. Astronomical information can be obtained from binary stars. By observing short period binaries using both spectroscopy and interferometry, we can determine the individual masses and orbital parallaxes of the objects based on their corresponding orbits. Spectroscopic binaries with double-lines are therefore fundamentally important to optically resolve. To determine the required telescope aperture for the resolution of a spectroscopic binary, we developed a specific algorithm. We determined the most probable maximum and minimum separations between each spectroscopic binary based on photometric and spectroscopic information. Thus, we also determined the different physical parameters of each system by using the calibrations we obtained in our study. Based on optically resolved spectroscopic binaries with both spectroscopic and visual orbits, the methodology presented here was successfully tested.

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

1. Introduction

A binary star consists of two stars orbiting the same mass center due to gravitational attraction. It can be considered a primary movement when a fixed motion is made around the center of mass, whereas a relative motion (secondary movement) can be considered a secondary movement. According to estimates, many stars are binary or multicomponent systems with three to four components (Al-Wardat et al., 2017, Duquennoy & Mayor, 1991, Raghavan et al., 2010). Astrophysics uses binary stars (BSs) for a variety of purposes. The stellar structure model, the star's evolution model, is considered a crucial test-bed for the development of a stellar structure model. There are many reasons why astronomy and astrodynamics are interested in binaries and multiple stars, but the most important reason is that stellar masses can be determined from their orbits and parallaxes. Studies of star evolution are fundamentally affected by their mass. Other physical parameters of interest are also obtainable, including luminosity and orbital elements, as well as sizes, parallaxes, and orbital elements (Al-Tawalbeh et al., 2021, Docobo et al., 2018, Hussein et al., 2022).

Space missions such as CoRoT, Kepler, and K2 can find exoplanets by searching for main sequence and pre-main sequence stars. BSs are ideal environments for looking for exoplanets. The three main types of binary systems are astrometric, spectroscopic, and eclipsing. A technique that determines the mass of a system is difficult. Since speckle interferometry was introduced 50 years ago, it has been used by researchers around the world for effective and accurate observation of binary stars. The astrometric binary and the

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double-lined spectroscopic binary are two types of binary systems that correlate with the masses of their components. We can determine the total mass of the system in AB by determining the orbit solution with known parallax. When the SB2 orbital solution is combined with the SB2 mass ratio, the three-dimensional orbit, mass, and parallax of the orbit can be calculated. Gaia data release (Gaia DR2) found systematic errors in astrometric parallaxes for bright stars, so such parallaxes were thought to be an effective verification method for them. This research method has been used in many publications over the years to determine physical parameters by combining each technique. Two double-lined spectroscopic binaries HD 6840 and HD 130669 were determined with precision in this study (Abushattal, 2017, Abushattal et al., 2019a, Docobo et al., 2017).

A number of spectroscopic binaries, SB, have been resolved using high resolution techniques since the 1970s. As a result of the SB2 orbits and the visual orbits, we can determine the mass and parallax of the components (the ratio using SB2 orbits and the sum using visual orbits).

In spite of this, we should consider the following questions before preparing the SB list to be resolved by a particular telescope. Could you please give us an estimate of what size telescope we would require in each case? How should we prepare a list for our telescope? To answer these questions, SB (double-lined) with a known orbit and parallax will be considered in this paper. As a result of our analysis, we propose the maximum and minimum angular separation for each of these SB using a three-dimensional model. Additionally, we provide the most probable values of these systems' physical parameters (spectral type, magnitude, and mass). In the first place, it is possible to calculate the masses of each component based on their spectroscopic orbits, composite spectrums, and apparent magnitudes of the whole, then the visual orbit can be calculated. Calculate the maximum and minimal angular distances between the components by drawing the apparent orbit and calculating the maximum and minimal angular distances. The tables corresponding to the calibrations used in this study are also described in the same section. In addition, we examine other systems and determine the telescope size necessary to resolve them optically.

The binary system serves as a suitable environment to observe many physical processes: mass loss, mass exchange, component variability the Nova phenomenon, the Flare phenomenon, X-ray binaries, etc. A dynamical approach includes perturbations, discovering dark components, such as brown stars and exoplanets, and calculating orbits (Abushattal et al., 2019b, Taani et al., 2019a,b, 2020). In 50% of multiple stars, the main sequence and pre-main sequence stars form BSs, which make BSs an ideal environment for discovering Earth-like planets via space missions like CoRoT, Kepler, and TESS. Due to the stages of star formation, multiple stars often contain the most massive exoplanets Exoplanets are often found in binary star systems, and binary stars are powerful hosts of many exoplanets. Habitability and stability are two parameters that depend on a binary star's properties. In this work, the main objective is to determine the mass of each planet, the semi-major axis, luminosities, and temperatures, which are the most important parameters for this work

2. Methodology for Double-lined Spectroscopic binaries (SB2)

A double-lined spectroscopic binary is one where two stars are too close together for their spectra to be resolved separately. In this binary, a specific spectral line of some element shows up twice in the (combined) spectrum. Due to their different wavelengths, the Doppler shifts indicate the relative radial velocity of stars, which is characteristic of orbital cycles. Observations show a cyclic pattern of peaks and valleys over time, single during orbital times with no radial velocity difference between the stars, and two during orbital times with radial velocity differences. Based on the relative radial velocities, we can estimate the smaller companion's mass, based on the spectral class.

If the spectral lines of both components are present in the observable spectrum and the orbit and parallax are known. However, we have additional information for the SB2. Indeed, the orbital parameters are P, e, T, $A_1 = a_1 \, sin\, i$, $A_2 = a_2$, and ω_1 or $\omega = 180^\circ + \omega_1$. The result is:

$$\frac{A_2}{A_1} = \frac{a_2}{a_1} = \frac{\mathcal{M}_1}{\mathcal{M}_2} = q, \tag{1}$$

and the mass ratio, q, is known.

Hereafter, we will suppose that if the spectroscopic binary is a double-lined SB2, then Δm is less than 1.5 or 2.0 (depending on the observational instrumentation). It is even possible that, in a few cases with $\Delta m = 2.5$, it may also be an SB2. This is not a problem for our methodology because it selects the solution by means of q.

Application of the methodology to the SB2, BD+52 1332 (HD 74089, HIP 42870) We will calculate the physical and orbital properties of binary stars using the Edward method, starting with their spectral type. In **?** the same method was used, but the starting point was to calculate the absolute magnitude based on astrophysical relations for the selected systems using parallax and apparent magnitude.

The double-lined binary BD+52 1332 (HD 74089) has a period of 1231.9 days. A Hipparcos parallax of 1.85±1.05mas and a Gaia parallax of 3.11 ± 0.24mas are the values of the two parallaxes. A late-type giant star has color indices of V = 8.53, B-V = 0.88, J-H = 0.482, and H-K = 0.125. Based on the spectral types of the components, Griffin (2014) identified the binary as G8III and G2III-IV. As reported in the Henry Draper Catalogue, Simbad has a spectral type of K0. Strairzys and Lazauskaite's paper provides a K0III spectral type by analyzing the color indices (Straizys & Lazauskaite, 2009).

In February 2012, the Cambridge Coravel spectrometer used to observe the radial velocity of HD$\dot{7}$4089 for the first time. It took about 11 months of observation were required to establish the radial velocity of the second component. For primary and secondary components, Griffin used 39 and 20 observations, respectively, to determine the orbital elements (Griffin, 2014).

Table 1. HD 74089. Physical and orbital parameters

Sp type	K0III
V_T (mag)	8.53 ± 0.01
π_{Hip} (mas)	1.85± 1.06
π_{Gaia}(mas)	3.11 ± 0.24
P (days)	1321.9126 ± 0.0017
T $_{(MJD)}$	56255.501 ± 0.016
e	0.0 ± 0.0
$a_1\sin(i)$(Gm)	14.11± 0.07
$a_2\sin(i)$(Gm)	15.36± 0.19
ω_1 (degree)	0.0± 0.0
q($\mathcal{M}_1/\mathcal{M}_2$)	1.0880 ± 0.0144

As a result, we consider HD 74089 to be K0III, with an absolute magnitude of 0.53. In the case of K0III, the mass of each component is 1.91 and the Δm is 0.42 until we reach a value of $\Delta m = 0.0$ (Edward's step = 0). This value has an absolute magnitude of 0.53 for both components. In agreement with Griffin: 1.088 ± 0.014, the ratio of the masses is 1.00 ± 0.57. See Table 3.9 for cases where the delta value was different.

According to the inclination, there is a minimum and maximum separation of ρ''_{max} =0.00080±0.00007, and ρ''_{min} = 0.00041±0.00040, respectively. If HD 74089 is to be resolved optically, a much larger telescope array is required than 147m.

Table 2. Orbital inclination and intermediary parameters as a function of Δm for HD 74089

Δm	S	M_1	M_2	Sp$_1$	Sp$_2$	$\mathcal{M}_{1(\mathcal{M}_\odot)}$	$\mathcal{M}_{2(\mathcal{M}\odot)}$	$a_{(A.U)}$	q $_{(m_1/\ m_2)}$
0.0	0.00	0.50±0.07	0.50±0.07	K0III	K0III	1.90±0.42	1.90±0.41	0.236±0.001	1.000±0.63
0.5	0.19	0.33±0.07	0.81±0.08	K1III	A2IV	1.84±0.40	2.63±0.25	0.255±0.001	0.700±0.31
1.0	0.29	0.23±0.05	1.22±0.06	K2III	A4IV	1.70±0.28	2.29±0.19	0.246±0.007	0.75±0.30

Name	$\pi_{Hip(mas)}$	$\pi_{Gaia(mas)}$	$m_{(mag)}$	Sp	Sp$_1$	Sp$_2$	$\mathcal{M}_1(\mathcal{M}_\odot)$	$\mathcal{M}_2(\mathcal{M}_\odot)$
HIP 12623	41.34±0.43	-	4.92	F9V	F9V	G3V	1.16±0.03	1.04±0.04
HIP 20087	18.50±0.50	-	5.63	F0V	A9V	F4V	1.69±0.03	1.38±0.03
HIP 42870	1.85±1.06	3.11±0.24	8.53	K1III	K1III	K0III	1.89±0.42	1.91±0.42

Table 3. Physical Parameters SB2

Table 4. Dynamical Parameters For SB2

Name (HD)	$a_{(AU)}$	$a_{1(AU)}$	$a_{2(AU)}$	$i_{(degree)}$	ρ(mas)	D (m)
HIP 12623	1.227±0.116	0.572±0.045	0.649±0.061	56.3±3.4	0.0457±0.0032	2.6
HIP 20087	7.380±0.542	3.264±0.246	4.116±0.393	55.9±3.2	0.1576±0.0126	1.0
HIP 42870	0.238±0.001	0.118±0.023	0.118±0.023	59.0±3.6	0.0008±0.0001	147

3. Stability

Stability is a very difficult concept to define. As a result of a variety of initial conditions, physical and mathematical theorems, and different constants, Astronomy has at least 50 concepts related to stability (Szebehely, 1984). Our definition of stability is characterized by the condition of no significant variation of orbital parameters over time (eccentricity, semimajor axis, and inclination). This section investigates three double-lined spectroscopic systems and determines their probable stable regions. We can determine the stability of planetary orbits around binary systems based on the empirical expression of (Holman & Wiegert, 1999) by observing the ratio between the mass and eccentricity of the system for two types of orbits: the inner (S-type) and the outer (P-type) of the orbit. During the 1980s, Dvorak (1984) described three types of stable orbits for planetary systems in binary systems:

- The satellite orbits (S-type) involve the planet orbiting around one of the binary's components,
- The planet-type orbits (P-type). The planet orbits the binary star around both components. We will say that it is a circumbinary planet, and
- The librator-type orbits (L- type). The stable orbit is around the Lagrangian points (which is stable only for the mass ratio, $\mu = \mathcal{M}_2/(\mathcal{M}_1+\mathcal{M}_2)$, $\mu \leq 0.04$) (Dvorak, 1984).

Holman - Wiegert empirical expression. Based on two values, the ratio of mass to eccentricity of the system (especially in the case of the P-type) Dvorak determined the stable zone in three-body problems. As a function of the mass ratio and semimajor axis, Holman - Wigeret came up with the same expression as Dvorak in 2007. For both types of orbits, (S-type) and (P-type), they developed the expressions below based on the results of the */alpha* Centauri system (Wiegert & Holman, 1997). They used least-squares fit data with the binary conditions as 0.1$\leq \mu \leq$ 0.9, and 0.0$\leq$ e $\leq$ 0.8 for the S-type, and 0.1$\leq \mu \leq$ 0.5, 0.0$\leq$ e $\leq$ 0.8 for P-type. The eccentricity (e), the longitude of the ascending node (Ω), the inclination (i), and the argument of perihelion (ω), were considered equal zero (Holman & Wiegert, 1999). The expression for the S- type (the inner region) 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:

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

Table 5. Physical parameters for the 13 double-lined spectroscopic binaries

Name	e	$\mathcal{M}_1(\mathcal{M}_\odot)$	$\mathcal{M}_2(\mathcal{M}_\odot)$	$a_{(A.U)}$
HIP 12623	0.663±0.002	1.18±0.03	1.04±0.04	1.221±0.116
HIP 20087	0.167±0.004	1.74±0.03	1.38±0.03	0.738±0.542
HIP 42870	0.0	1.91±0.42	1.91±0.42	0.237±0.001

Table 6. The stability limits for exoplanet orbits around each component and both components (circumbinary planets), in the 13 double-lined spectroscopic binaries

Name (HD)	$a_{1S_{max}(A.U)}$	$a_{1S_{min}(A.U)}$	$a_{1P_{min}(A.U)}$	$a_{2S_{max}(A.U)}$	$a_{2S_{min}(A.U)}$
HIP 12623	0.1134	0.0011	**4.473**	0.1073	- 0.0104
HIP 20087	0.150	0.136	**2.140**	0.175	0.162
HIP 42870	0.065	0.064	**0.539**	0.065	0.064

Exoplanet orbits, especially those in stellar binary systems, are difficult to determine due to their instability

Table 7. Stellar parameters used to study the habitable zone for the 13 double-lined spectroscopic binaries

HD	$a_{(A.U)}$	Sp_1	Sp_2	T_1(K)	T_2(K)	$L_1(L\odot)$	$L_2(L\odot)$	$\mathcal{M}_1(\mathcal{M}_\odot)$	$\mathcal{M}_2(\mathcal{M}_\odot)$
HIP 12623	1.222±0.116	F8V	G2V	6160	5811	2.21	1.30	1.18±0.03	1.04±0.04
HIP 20087	7.380±0.542	A8V	F3V	7682	6782	9.70	4.47	1.74±0.03	1.38±0.03
HIP 42870	0.230±0.001	K0III	K0III	5282	5282	39.81	39.81	1.91±0.42	1.91±0.42

Table 4 shows the following data: Column 1, present the name of the binary (HD number); Column 2, the eccentricity (e); Column 3, the semimajor axis of the binary in astronomical units (A.U); Column 4, includes the minimum and the maximum values of Δm for each binary; Column 5 and 6, the masses for each component in solar mass ($\mathcal{M}_\odot$).

Tables 6, and 7 list, the name of the binary (HD number) in Column 1. Columns 2 and 3 indicate the stability limits of the exoplanets orbits in the case of an S-type orbit around the main component (as a minimum value ($a_{S\,min}$) and maximum value ($a_{S\,max}$)) in astronomical units (A.U), Column 4 shows the stability limits for the exoplanet in the case of a P-type orbits where bold values indicate a minimum value ($a_{P\,min}$) (especially for the SB1 because different Δm are possible) also in astronomical units (A.U); and Columns 5 and 6 contain the same information as Columns 2 and 3 but, in this case, for orbits around the secondary component.

On the other hand, in order to understand the orbit stability around each star, we have to mention here that the stability is given between two values of the distance: the first one is $a_{S\,max\,(A.U)}$, which represents the largest distance around the star at which the orbit of the exoplanet is stable even with the existence of the second component. The second value $a_{S\,min}$ $(A.U)$, represents the closest separation to the star where the existence of the stable orbits of exoplanets is possible in this situation the stability is not guaranteed, we have to take into account the spectral type and the size of the star because, in some cases, the radius of the star is very close to the minimum value for the stability which means that the stability analysis by Holman and Wiegert cannot be used as the restricted three-body problem is not a valid model. Moreover, in some cases, the maximum stability limit might be in side the star.

4. Habitability

An interesting definition of habitability was introduced by Cockell of the UK Centre for Astrobiology, University of Edinburgh, which describes the environment as capable of supporting metabolic activities for at least one known organism, and as such supporting its survival, growth, maintenance, or reproduction processes. (Cockell et al., 2016). The best state for the water to support the basic processes of life, the liquid state, requires suitable temperature on the exoplanet; not cold or hot, and its temperature depends on various parameters, internal parameters such as radio activity and the components of the atmosphere. Depending on the distance from the nearest star, the external parameter depends on the source of the radiation. It is first necessary to determine the habitable zone where liquid water can be found when searching for exoplanets. Around a single star or around a binary star, the HZ appears as a spherical shell. Several parameters must be taken into consideration in order to determine the habitability of a binary system: ($\mathcal{M}_1$, $\mathcal{M}_2$), the period (P), the eccentricity (e), and the semimajor axis of the exoplanet orbit (a)(Mason et al., 2013). Because of the gravitational force generated by the host star, the semimajor axis and eccentricity of the exoplanets can change because it migrates out of the habitable zone due to the tidal force. As a result, it is generally less likely that exoplanets will be habitable in the future (Barnes et al., 2007, Barnes et al., 2008), and Over time, habitability changes..

When two stars are separated by less than 50 AU, especially in cases of binary systems, the gravity of one star affects the HZ and stability around the exoplanet, causing perturbations in its orbit and ability to contain liquid water. (Eggl et al., 2012).

The following parameters are fixed in order to determine a habitable zone for spectroscopic binaries: the temperature derived from the table relating to spectral types developed by (Gray, 2005) , the mass derived from our previous chapter methodology, and the luminosity determined by the luminosity-absolute magnitude relation.

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

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).

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A website `http://astro.twam.info/hz/` devised by Tobias Muller and Nader Haghighipour in 2013 determines the habitable zone for single stars, double stars, and multiple stars (Müller & Haghighipour, 2014). As well as a habitable zone calculator, this website contains tables, plots, and videos that simulate the motion of an exoplanet around a star. On this website, you will find four different models: 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. This the same method that we used previously to describe the radii of the stability around single-lined and double-lined spectroscopic binaries.

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 (see Tables 4.5, 4.6), which allow us to use a methodology of (Müller & Haghighipour, 2014) to describe the habitable zone around the stars of our sample of 30 spectroscopic binaries. Tables 4.5 and 4.6 list in Column 1, the name of the star; Column 2, the semimajor axis of the binary in astronomical units (A.U); Columns 3 and 4; the spectral type for the primary component and the secondary; Columns 5 and 6, the temperature of each component in Kelvin degrees (K); Columns 7 and 8, the luminosity of each component in the solar luminosity ($L_\odot$), and Columns 9 and 10, the mass of the each component in solar mass ($\mathcal{M}_\odot$).

We take into account that liquid water exists in an environment with an atmospheric pressure of 1 atm within a temperature range of 273 K to 373 K which is dependent on the distance from the center-mass of the system and the luminosity of the stars. The habitable zone was calculated using the (Müller & Haghighipour, 2014) method and we classified these results into three subtypes depending on the width of the habitable zone (WHZ) in AU compared with the width of our solar system which is about 0.7 AU (Kopparapu, 2013). Taking into account the difference in the class of each system, 50% of our results show habitable zones within the following ranges: $0.5 \leq \text{WHZ} \leq 2.5$, 23%, 2.5 ¡ WHZ ≤ 5, and 27 %, 5 ¡ WHZ. This WHZ yields an increased possibility of the existence of liquid water, especially around giants stars. Unfortunately, it also expands the area to search for habitable exoplanets requiring more observing time.

5. The Graphics of the Stability and Habitable Zones

After identifying stability zones and habitable zones in the previous two sections, we combine these two parameters to find stable orbits within habitable zones. The possibility of having an exoplanet with liquid water is possible when there is a match between the habitable and stable areas.

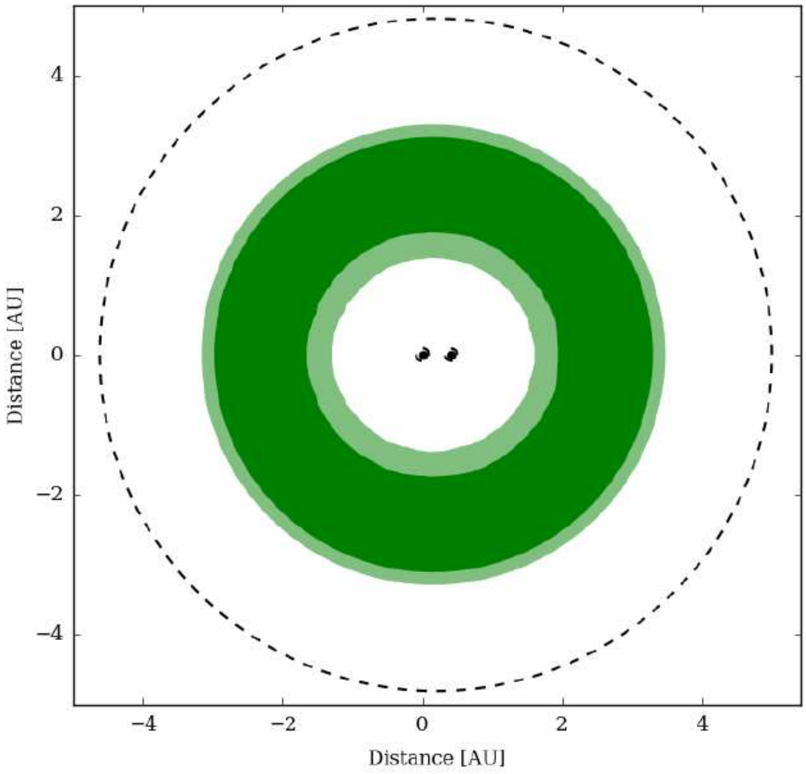

Figure 1. Stability and Habitable Zone for HIP 12623 system

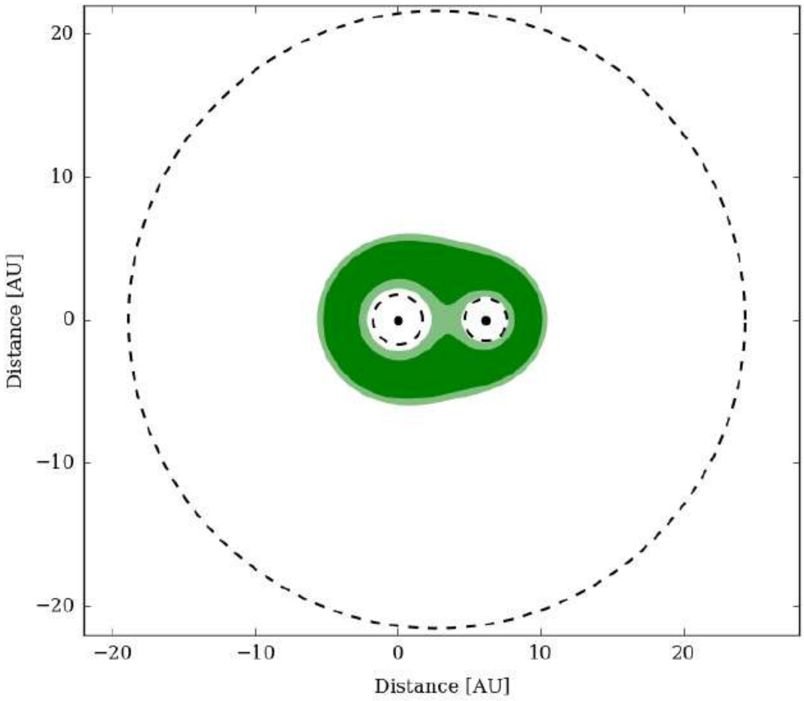

Figure 2. Stability and Habitable Zone for HIP 20087 system

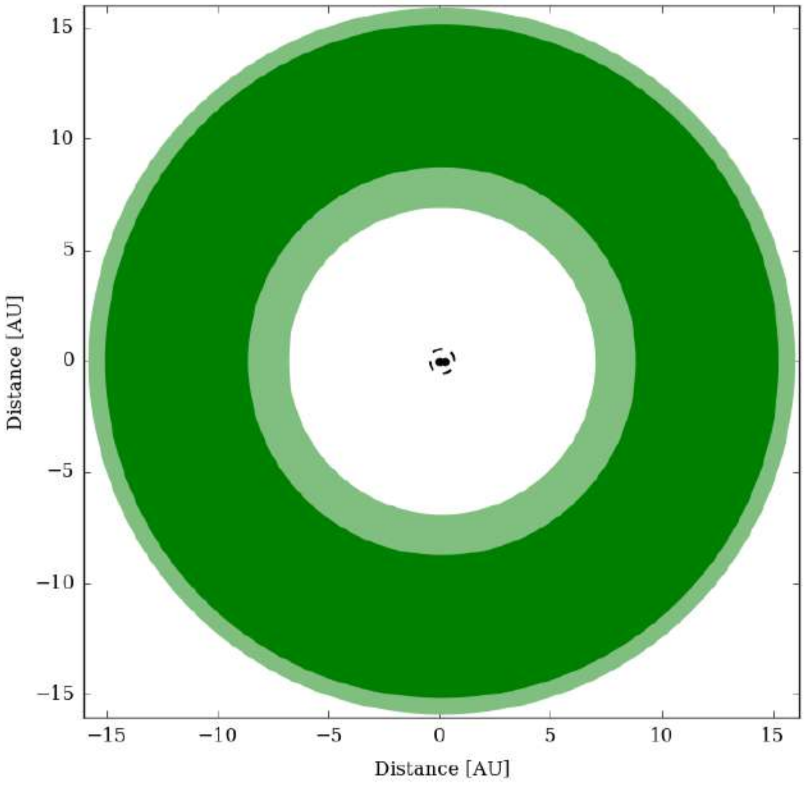

Figure 3. Stability and Habitable Zone for HIP 4287 system

6. Conclusions and Future Work

We present a spectro-interferometric analysis and calculate the physical and orbital properties of three binary stars, starting with their spectral type, and then analyzing them using the Edward method. This new method has been developed for three double-lined spectroscopic systems with recent orbital calculation results to calculate the stability and habitability, astronomical parameters such as orbital parallax and mass and semi-major axis. In this way, we can determine whether the host system is stable and habitable enough to host an exoplanet or the existence of earth-like planets.

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