Habitable Zones with Stable Orbits for Planets around Binary Systems

Luisa G. Jaime¹, Luis Aguilar², and Barbara Pichardo¹ *

¹Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo. postal 70-264, Ciudad Universitaria, México
²Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo. postal 877, 22800 Ensenada, México

Accepted. Received ; in original form

ABSTRACT
A general formulation to compute habitable zones for binary stars is presented. We extend the simple formulation of the known concept: circumstellar habitable zone for single stars, to the case of eccentric stellar binary systems, where two sources of luminosity at different orbital phases contribute to the irradiance of their planetary circumstellar and circumbinary regions. Our approach considers binaries with eccentric orbits and guarantees that orbits in the computed habitable zone remain within it at all orbital phases. We apply this formulation to calculate habitable zones for binary stars of the solar neighborhood with known orbital parameters. Regions of stable, non-intersecting orbits, supported by invariant loops have been determined using the results of Pichardo, et al. 2005 and 2008, together with their habitable zones, are calculated for 51 cases, including some with discovered planets.

Formulæ and interpolating tables are provided, so the reader can compute the boundaries of the habitable zones for an arbitrary binary system, using the stellar flux limits they prefer. Together with the formulæ provided for stable zones, these allow the computation of both regions of stability and habitability around any binary stellar system. We found just that 50% of the cases we take can satisfy both restrictions, this is a very important constriction to binary systems, nevertheless our conclusion shows this kind of systems must be considered as strong candidates in the search for habitable planets and allow us to point some binaries as viable candidates.

Key words: binaries: general, planets, habitability

1 INTRODUCTION
The discovery of hundreds of extrasolar planets has hurled the topic of planetary studies into centerstage: planet formation, planetary dynamics, planetary geology, etc.; among these studies, the question of planet habitability is of great interest, even if no hard data beyond Earth exists, yet. The quest for life on other planets started long ago when in the 60’s, Frank Drake used the 85-foot radio telescope in West Virginia, hoping to detect an extraterrestrial signal (Drake 1961). However, extraterrestrial life, if it indeed exists in the neighborhood of the Sun, is most likely of a basic type (e.g. microbial). Although a new emerging view is that planets very different to Earth may have the right conditions for life, which increases future chances of discovering an inhabited world (Seager 2013), it is a good first step along this endeavour to find out if conditions propitious to Earth-like planetary life (the only type we know for sure so far) exist.

Even in the case of Earth, life exists in many diverse environments, from scorching deserts to the eternal darkness of the ocean depths, and even deep within Earth’s crust. Confronted with this bewildering diversity of environments, we must look for the most basic ingredients, like liquid water. On the other hand, our observational limitations to detect the most important habitability indicator: water vapour on terrestrial-like exoplanets, reduces our possibilities of finding habitable planets. Up to now, we have been able to define a general habitable zone around single stars as the only guide for astronomers to focus future observational efforts of exoplanet discovery (Seager 2013). But given the fact that most stars appear to be part of binary and multiple systems, we must extend the habitable-zone concept to those cases.

The condition for the existence of liquid water on the surface of a planet (Bains 2004), is the usual defining condition for what is now called the circumstellar habitable zone (CHZ). Hart (1979) studied the limits of the CHZ in late type stars and concluded that K dwarfs have a narrow CHZ and later dwarfs have none at all. However, other studies that include among other things, atmospheric radiative transfer modeling, have come with a more optimistic and, rather complicate outlook (e.g. Doyle et al. (1998)). In this case, habitability seems to be a very planet-specific matter (Seager 2013). For example, the habitable zone calculations defined, for example for a dry rocky planet, with a minimum inner edge of about 0.5
AU, for a solar-like host star (Zsom et al. 2013), out to 10 AU for a planet with an H2 atmosphere and no interior energy, around a solar-like host star (Pierrehumbert & Gaidos 2011), and even possibly out to free-floating habitable planets, with no host star, for planets with thick H2 atmospheres (Stevenson 1999).

In the present work we will use Kopparapu et al. (2013) definition of habitable zone around single stars and extend it to the case of binary stars. As such, this is a simple definition of the habitable zone based on stellar flux limits. Some of the more complicated (and realistic) effects that pertain to particular situations, can be incorporated into this simple criterion by the use of “corrective factors” applied to the stellar fluxes that define the limits of the habitable zones. An example of this is provided by (e.g. Kaltenegger & Haghighipour 2013), who introduces a factor called “spectrally weighted flux”.

Studies like the previous ones, have been applied traditionally to single stars or brown dwarfs, however, most low-mass main-sequence stars are members of binary or multiple systems (Duquennoy & Mayor 1991; Fischer & Marcy 1992), and in particular in the Solar Neighborhood, the fraction goes up to 78% (Abt 1983). This suggests that binary formation is the primary branch of the star formation process (Mathieu 1994). Additionally, several types of planets have been discovered in circumstellar orbits, even in close binary systems, where the effect of the stellar companion might be of great importance (Dumusque et al. 2012; Chauvin et al. 2011; Muterspaugh et al. 2010; Correia et al. 2005; Zucker et al. 2004; Hatzes et al. 2003; Queloz et al. 2000), and also in circumbinary discs (Doyle et al. 2011; Welsh et al. 2012; Orosz et al. 2012a; Orosz et al. 2012b; Schwamb et al. 2013). For a review on the subject see Haghighipour (2010); and Kaltenegger & Haghighipour (2013).

We provide in this work a general theoretical formulation to calculate the equivalent of the Kopparapu et al. (2013) habitable zone for single stars, but for binary systems (see section 2). This formulation is expressed in formulae and interpolating tables that the reader can apply to any specific case. Our work also considers binary systems in eccentric orbits and guarantees that orbits within the computed habitable zones remain so, at all binary orbital phases. We only consider approximately circular planetary orbits. We combine our work with the work of Richardo et al. 2005 and Pichardo et al. 2009, who found the extent of stable, non-intersecting orbits around binary systems, based on the existence of sturdy structures in the extended phase-space of the system (the so called “invariant loops”). We have then applied these to the majority of main sequence binary systems in the Solar Neighborhood with known orbital parameters and present our results. These constitute regions were we think it is most likely to find planets suitable for life in these binary systems.

The stability of the orbits is very important in order to consider planet habitability. Some authors like Kane & Hinkel (2013), have taken into account orbit stability, but not for long times. Here it is important to emphasize that the existence of invariant loops guarantees the stability of orbits for all times and not just during the integration span, as long as the binary parameters (stellar masses, semi-major axis and orbital eccentricity) do not change. Their stability is given by the constants of motion that support them. The orbit integration is only used to identify these structures in extended phase-space (for details see Richardo et al. 2005; Maciejewski & Sparke 2000; Maciejewski & Sparke 1997; Arnold 1984; Lichtenberg & Lieberman 1992).

When we were getting ready to submit this paper, we saw a work by Cuntz (2013) that just appeared in the ArXiv database. This work is very similar to the first part of ours. In fact, our equation [6], deduced to find the limits of the BHZ, is the same, cast in a different form, as the one that this author considers. Although the details of the approach are different, the results of this part are similar. Although Cuntz mentions the nice work of Holman & Wiegert (1999) for the orbital stability criterion, that approximation presents complications to calculate stable zones toward high binary eccentricities. In this work, we rely on our own work on invariant loops for any eccentricity and mass ratio and also include it here to find plausible habitable zones in binary stellar systems. In the second part of this work we also provide a sample of binary systems of the solar neighborhood (the whole sample of binary stars, in the main sequence, with all orbital parameters known at the present time in literature), with their habitable zones computed using the approach in this work for habitability and planets orbital stability.

This paper is organized as follows. In Section 2 a detailed description of the formulation used to calculate the habitable zones around binaries is provided. In Section 3 we present the stability criteria used in this work. Section 4 is devoted to particular cases and the construction of the whole table of binaries of the solar system with known orbital parameters for stars in the main sequence. Finally, our conclusions are given in Section 5.

2 HABITABILITY ZONES AROUND BINARY STARS

A common definition of the CHZ uses limits in the radiative stellar flux at the planet (e.g. Kasting et al. 1993):

$$I_o \leq I(r) \leq I_i,$$  

where the local flux is given by the stellar luminosity divided by distance squared: $I = L/r^2$, and $I_o$, $I_i$, define the outer and inner boundaries of the CHZ, respectively.

The CHZ thus defined is a thick spherical shell that surrounds the star, whose thickness and size depend on the star’s luminosity. However, a good fraction of stars in the solar neighborhood are part of binary systems. The fact that planets have already been discovered within binary systems, makes it necessary to extend the simple definition of the CHZ to the stellar binary case.

In this section we extend the simple CHZ condition for single stars given by the previous equation, to the case of stellar binary systems. In this case we have two sources of luminosity at positions that change with the binary orbital phase. It may be thought that in this case it is simply a matter of applying the equation twice, once for each star. However, this naive approach is not correct, since there may be regions where, although within the individual CHZ for each star, the combined irradiance of both stars may push the region out of the combined habitable zone.

Since what matters is the total combined irradiance at a given point, we should add the individual stellar fluxes in the CHZ condition given by equation (1), to arrive at the condition for the binary habitable zone (BHZ). The total stellar flux is given by:

$$I(x, y) = L_T \left[ \frac{(1 - \lambda_x)}{(x - r_p)^2 + y^2} + \frac{\lambda_x}{(x - r_s)^2 + y^2} \right],$$

here $L_T$ is the total binary luminosity and $\lambda_x$ is the fractional contribution of the secondary star to it. $x$ and $y$ are cartesian coordinates in the binary orbital plane and $r_p$ and $r_s$ are the primary and secondary star distances to their barycenter. The $x$-axis contains both stars.

The edges of the BHZ are set by two stellar flux isopleths...
and the resulting shape is more complicated than that of the CHZ. Figure (1) illustrates a particular example: the gray regions are the BHZ. Dashed lines indicates possible planetary orbits that are not fit for life, while solid lines indicate safe orbits (we have approximated the planetary orbits as circles centered in either star, or the barycenter). Notice that for an orbit to be safe, it must remain within the BHZ at all times. In this particular case, there are safe circumprimary and circumsecondary planetary orbits, but no circumbinary ones.

In addition to the above complication, the separation between the stars will vary for the general case of binaries with elliptical orbits. First we will tackle the simpler case of circular orbit binaries.

2.1 Binaries in circular orbits

In the circular orbit case the star distances to the barycenter are given by:

\[ r_p = -(m_s/M)r_{12}, \quad r_s = +(m_p/M)r_{12}, \]

where the \( p \) and \( s \) subindices refer to the primary and secondary stars, \( m \) are the individual stellar masses and \( M \) is the total mass. Finally, \( r_{12} \) is the constant distance between the stars.

If we take the interstellar distance and total mass as units of length and mass, we can write the previous relation as:

\[ \eta_p = -q, \quad \eta_s = +(1 - q), \]

where \( \eta \) is dimensionless distance and \( q = m_s/M \) is the mass fraction due to the secondary.

A similar scaling in luminosity can be accomplished adopting \( L_T \) as its unit. The dimensionless combined stellar flux is then:

\[ I(\eta_p, \eta_s) = \frac{(1 - \lambda_s)}{(\eta_p + q)^2 + \eta_s^2} + \frac{\lambda_s}{(\eta_s + q - 1)^2 + \eta_s^2}. \]

Figure (2) shows the value of the critical flux isopleth as a function of the secondary star luminosity fraction. Notice that \( I_c \) is symmetric with respect to \( \lambda_s = 0.5 \).

where \((\eta_p, \eta_s)\) are the corresponding dimensionless cartesian coordinates. Notice that \( I \) is completely set by the luminosity and mass ratios, its unit is \( L_T/r_{12}^2 \).

2.1.1 The critical flux isopleth

The shape of the \( I \)-isopleths changes from a single (circumbinary) to a double (circumstellar) contour at the critical isopleth (see figure 2). Its value is given by:

\[ I_c(\lambda) = \frac{(1 - \lambda_s)^{1/3} + \lambda_s^{1/3}}{((1 - \lambda_s)^{2/3} + \lambda_s^{2/3} - \lambda_s^{1/3}(1 - \lambda_s)^{1/3})^2} \] (5)

2.1.2 The three different BHZ morphologies

Depending of the value of the dimensionless stellar fluxes that define the CHZ (equation 1), with respect to the critical isopleth flux, the BHZ can have three different morphologies:

Case I: \( (I_c < I_o) \). This corresponds to 2 separate circumstellar habitable zones.

Case II: \( (I_s < I_c < I_o) \). This corresponds to a single circumbinary zone with two inner holes.
Case III: \((T_b < T_c)\). This corresponds to a single circumbinary zone with a single inner hole.

These cases are illustrated in figure[4]

Safe planetary orbits must be entirely contained within the BHZ. This means that we have to consider their shape, which introduces an added complexity we will not get into, so we adopt the simplifying assumption that planetary orbits are circles centered on either star (circumstellar orbits), or the barycenter (circumbinary orbits). Even with this simplification, a problem arises because the flux isopleths are not circles (see figure[4]), particularly close to the critical isopleth.

It is clear that the largest safe orbit must be entirely inscribed within the flux isopleth that defines the outer boundary of the safe zone. Similarly, the smallest safe orbit must be entirely circumscribed outside the inner boundary flux isopleth. We now examine these conditions for each case.

2.1.3 Case I

In this case we have two separate circumstellar habitable zones. The orbital radius of the largest safe planetary orbit is given by the smallest distance between the outer boundary isopleth and the corresponding star. This ensures that the orbit will remain within the outer boundary isopleth.

Similarly, for the radius of the smallest, circumstellar safe orbit, we must now consider the maximum distance from either star to the corresponding inner boundary flux isopleth, so the orbit remains outside it at all times.

The circumstellar isopleths are elongated along the \(\eta_x\) axis in the direction of the other star, while they are squashed in the opposite direction. This means that both, the outer and inner circumstellar orbital radii \(r_{os}\) and \(r_{is}\), respectively, correspond to the respective boundary isopleth intersections with the \(\eta_x\) axis (see figure[5]).

From equation \((4)\), setting \(\eta_y = 0\) and putting the star in question at the coordinate origin, we arrive at the following polynomial:

\[
I_0 r_s^4 - 2I_0 r_s^3 + (I_0 - 1) r_s^2 + 2\lambda r_s - \lambda = 0, \tag{6}
\]

where \(I_0\) is the dimensionless flux value that defines the BHZ boundary and \(r_s\) is either, the outer circumstellar orbital radius \(r_{os}\), or the inner one \(r_{is}\), depending on the solution we choose. Unfortunately, although 4-degree polynomials can always be solved by radicals, the solution in this case is quite cumbersome. We have decided instead, to list in table[1] some solutions. The first value at each entry corresponds to \(r_{os}\) (smallest value), the second to \(r_{is}\). We list results from the critical isopleth up to thrice its value only, because for larger values, the circumstellar boundaries are very close to the star and the single star CHZ criterion (equation \((1)\)) is sufficient. This is shown in figure[5] where the fractional error made in using the CHZ criterion individually for each star, instead of the true value obtained by solving equation \((6)\), is shown as a function of the flux value for the inner boundary. We can see that for values larger than those listed in table[1] the error drops well below 1%.

2.1.4 Case III

The considerations that define the largest and smallest safe circumbinary orbits are the same as for the previous case, except that this time we are dealing with boundary isopleths that surround both stars and the relevant extremal distances are with respect to the binary barycenter.

In this case there are two additional difficulties: the position of the isopleths with respect to the barycenter depends on the mass ratio too and their form, close to the critical one, is nowhere near circular.

For the outer boundary, the relevant distance is that from the barycenter to the closest point along the boundary isopleth. In general, this point is not along either axis (see figure[7]).

From equation \((4)\), we obtain the barycenter–isopleth distance. Minimizing this function, we get the orbital radius of the largest safe orbit:

![Figure 4. The three different BHZ morphologies. The illustration is for a binary with \(\lambda = 0.4\).](image)

![Figure 5. Circumstellar boundaries of the BHZ. The boundary isopleth is the dashed line. If this isopleth corresponds to the outer boundary, the largest safe orbit touches the isopleth on its \(\eta_x\) intersection opposite the other star (left solid circle). If the isopleth is the inner boundary, the smallest safe orbit touches the isopleth at the opposite \(\eta_x\) intersection (right solid circle). The case shown is \(q = 0.3\), \(\lambda = 0.2\) and the isopleth depicted is 1.0045\(I_c\). The primary star, which in this example is also the most luminous, is the one on the left.](image)

![Figure 6. Fractional error made using the CHZ criterion for a single star, instead of \(r_{is}\), as a function of the inner boundary flux value (in units of the critical flux value). The solid line is for the most luminous star (\(\lambda = 0.9\)), while the dashed line is for the less luminous star (\(\lambda = 0.1\)).](image)
The isopleth depicted is the outer circle. The case shown is the same as that of figure (5), except that the dashed line and the barycenter is at the coordinate origin. If this isopleth distances. The largest one is the boundary isopleth (in this case \(r^\lambda\)). To find the final inner circumbinary orbital radius, we now add the respective star to barycenter distance (equation (3)) to each root and compare the resulting barycenter to isopleth distances. The largest one is \(r^\lambda\).

As before, the solution is rather complicated and some values of \(r^\lambda\) are shown in table 2. For distant boundaries (small values of \(I_o/I_e\)), the isopleths become circular and converge to the BHZ criterion applied using the total binary luminosity. This can be seen in figure 8, where the fractional error made using the CHZ instead of the BHZ criterion is plotted for the \(\lambda = 0.9\) case. Again, for values beyond those listed in table 2 the error is very small.

In this case it may be that \(r^\lambda < r^\lambda\), which means that no safe circular orbits centered in the barycenter exist. However, a non-circular and sufficiently elongated orbit may remain within the BHZ, but this is beyond this study.

### 2.1.5 Case II

Case II is the most complicated, since we now have the possibility of both, circumpolar and circumbinary safe orbits. This is a mixture of the previous two cases and they have to be dealt separately.

For the circumpolar orbits, we use the procedure used for...
Figure 9. Circumbinary safe orbits in case II. The dashed line is the critical isopleth and the shaded area is the BHZ. The extremal safe circumbinary orbits are shown (continuous line circles). The example shown is for isopleth and the shaded area is the BHZ. The extremal safe circumbinary

Table 2. Some values of the star to outer boundary isopleth \( r_\star \) (negative real solution to equation (6) for \( I_b < I_c \))

| \( \frac{I_a}{I_c} \) | \( \lambda = 0.1 \) | \( \lambda = 0.2 \) | \( \lambda = 0.3 \) | \( \lambda = 0.4 \) | \( \lambda = 0.5 \) | \( \lambda = 0.6 \) | \( \lambda = 0.7 \) | \( \lambda = 0.8 \) | \( \lambda = 0.9 \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0.99            | 0.210           | 0.261           | 0.300           | 0.335           | 0.368           | 0.403           | 0.441           | 0.489           | 0.526           |
| 0.90            | 0.222           | 0.276           | 0.316           | 0.352           | 0.387           | 0.423           | 0.463           | 0.514           | 0.589           |
| 0.80            | 0.239           | 0.295           | 0.338           | 0.375           | 0.412           | 0.450           | 0.492           | 0.546           | 0.626           |
| 0.60            | 0.287           | 0.349           | 0.397           | 0.439           | 0.480           | 0.523           | 0.571           | 0.632           | 0.723           |
| 0.40            | 0.379           | 0.446           | 0.500           | 0.549           | 0.597           | 0.648           | 0.705           | 0.778           | 0.888           |
| 0.20            | 0.635           | 0.695           | 0.754           | 0.812           | 0.872           | 0.938           | 1.014           | 1.111           | 1.262           |
| 0.10            | 1.084           | 1.101           | 1.151           | 1.213           | 1.282           | 1.363           | 1.461           | 1.590           | 1.795           |
| 0.05            | 1.796           | 1.736           | 1.759           | 1.814           | 1.889           | 1.984           | 2.106           | 2.275           | 2.552           |
| 0.01            | 4.978           | 4.624           | 4.512           | 4.508           | 4.574           | 4.701           | 4.900           | 5.211           | 5.769           |
| 0.005           | 7.392           | 6.833           | 6.623           | 6.571           | 6.624           | 6.767           | 7.017           | 7.427           | 8.188           |
| 0.001           | 17.61           | 16.20           | 15.59           | 15.34           | 15.34           | 15.54           | 15.99           | 16.80           | 18.40           |
| 0.0005          | 25.27           | 23.24           | 22.33           | 21.93           | 21.88           | 22.13           | 22.72           | 23.84           | 26.07           |
| 0.0001          | 57.60           | 52.93           | 50.76           | 49.75           | 49.75           | 49.95           | 51.16           | 53.53           | 58.40           |

Figure (10) shows the result for a specific example. We have a primary G2V star with \( 1M_\odot \) and \( 1L_\odot \), while the secondary is a G8V star with \( 0.8M_\odot \) and \( 0.6L_\odot \). The stars are assumed to be

which we computed already), plus their respective star distance to the barycenter.

2.1.6 The habitability region

Tables 1 and 2 together with equation (7) and auxiliary relations, define the orbital radii of the largest and smallest circumstellar or circumbinary safe orbits.

The detailed procedure to find the limits of the BHZ is then as follows:

(i) From the binary components individual masses and luminosities, obtain the dimensionless mass fraction \( q \) and luminosity fraction \( \lambda \), the latter for both stars.

(ii) Get specific boundary radiative stellar flux values \( I_o, I_i \) (e.g. Kasting et al. 1993) and convert them to the dimensionless system we use here: \( \frac{I_i}{I_o} \) (normalized to total binary luminosity per square semimajor axis).

(iii) Given \( \lambda \) (either star), use equation (5) to find the value of the critical flux for this case: \( I_{crit} \).

(iv) If \( I_o > I_{crit} \) proceed to case I; if \( I_o < I_{crit} \), proceed to case III; else, go to case II.

(v) Case I: Two separate circumstellar habitable zones. Use table 1 to interpolate the \( r_{os} \) and \( r_{ib} \) orbital radii for each star using the appropriate value of \( I_b \).

(vi) Case II: One circumbinary habitable zone with two circumstellar inner edges. We have to solve the circumstellar and circumbinary zones separately.

(a) Circumstellar zones: Use table 1 to interpolate the \( r_{os} \) orbital radii for each star using \( I_o = I_i \).

(b) Circumbinary zone: Use equation (7) to get the outermost orbit radius \( r_{ob} \). For the smallest orbit, add to the \( r_{os} \) previously computed for each star their respective star to barycenter distances, the largest of the two is the radius of the innermost safe circumbinar orbit.

(vii) Case III: One circumbinary habitable zone whose inner edge surrounds both stars. For the outer boundary, use equation (7) to compute \( r_{ob} \). For the inner boundary, use table 2 to compute the distances of each star to its closest \( \eta_x \) intersection of the inner boundary isopleth \( r_\star \). To each add the barycenter to respective star distance using equation (5). The largest of the two is \( r_{ib} \).

1 We should remember that the Roche lobes, which are the regions of dynamical influence of each star, are not the same as the circumstellar regions defined by the critical flux isopleth.
account the true non-circular shape that stable orbits may have, nor does it take into account the possible variation in their size as a function of binary orbital phase. These effects may arise close to the critical isopleth, however, this largely coincides with the loop gap between circumstellar and circumbinary stable orbits.

3 STABILITY CRITERION

In this paper we have employed the criteria of Pichardo et al. (2005) and Pichardo et al. (2009) for circumstellar and circumbinary stable orbits respectively. The same approach was used in Jaime et al. (2009), where stability zones were studied for binaries of the solar neighbourhood. Under this approach stable zones are defined by invariant loops (see Pichardo et al. (2005) and Pichardo et al. (2009) for details) and are given by,

$$R_i = R_i^{Egg} (0.733(1 - e)^{1.2} q^{0.07}) ,$$

(11)

That represents the radius for the most exterior stable orbit around each star. In a similar manner, the inner viable radius for circumstellar stable orbits is,

$$R_{CS} \approx 1.93a \left(1 + 1.01e^{0.32}\right) (q(1 - q))^{0.043} ,$$

(12)

where $a$ is the semimajor axis of the binary, $e$ the eccentricity and $q$ is the mass ratio (see eq. (3)).

Finally, in equation (11), $R_i^{Egg}$ is the approximation of Eggleton (1983) to the maximum radius of a circle within the Roche lobe, given by,

$$R_i^{Egg} = \frac{0.49a q^{3/3}}{0.6q_i^{2/3} + \ln(1 + q_i^{1/3})} ,$$

(13)

in this equation $q_i$ is defined by $q_1 = M_1/M_*$ and $q_2 = M_2/M_*$.

For the general eccentric case, one most consider a shift of the center of the minimum radius for stable circumbinary orbits, $R_{CB}$ (eq. (12)). This shift is given by,

$$R_{sh} = -3.7 a e^{0.8} (0.5 - q) \left[q(1 - q)^{1/4}\right] .$$

(14)

It is important to stress that the orbits defined by equations (11) and (12) represent stable orbits form by non self-intersecting loops, where gas and planets could settle down in long term basis.

4 PARTICULAR CASES

As we have mentioned, the restriction of dynamical stability within habitability zones is one of the goals of the present paper. In order to show how this approach allows us to find candidates in the search for habitable planets, in this section we apply our method to 51 binary systems with known orbital parameters for main sequence stars. Most of the cases are eccentric binaries, thus we apply the method atperiastron and apoastron. Once we have these two calculations, we compare both and take, conservatively, the most restricted circular edge. It is worth to mention that it is important to compute it in both locations because we do not know a priori in wich case the binary will be located (i.e., if the habitable zone will be circumstellar or circumbinary). Given this, the restriction at periastron or apoastron acts in different ways for zones I, II or III,
and the case can even change from one to another, and this should be taken into account.

All cases considered in this paper are taken from [Jaime et al. (2009)], according to literature, located in the main sequence. We have applied the classical luminosity-mass function [Cox (2000)] in order to obtain the luminosity for each star. Orbital parameters are the same as the ones considered in [Jaime et al. (2009)].

Another important issue that must be considered, is the circumbinary disc center shift, produced by eccentric binary systems (eq. (13)). In high eccentric cases this shift might become relevant when calculating the circumbinary orbits inside of the habitable zone.

Table 3 shows the results for the 51 objects at periastron, column 1 is the Hipparcos name, column 2 is an alternative name, column 3 shows the particular habitable case resulting for the binary, columns 4 and 5 contain the inner and outer habitable radii for the primary star and columns 6 and 7 are the same but around the secondary star. Finally columns 8 and 9 provide the inner and outer habitable radii in the circumbinary case. Table 4 shows the same as Table 3 but at apoastron.

Table 5 shows orbital parameters for each binary, columns 1 and 2 are the HIP name and alternative name, column 3, 4, 5 and 6 are semimajor axis, eccentricity, primary and secondary masses respectively. Column 7 shows the outer stability radius around the primary star while column 8 shows the same but for the secondary star of the binary. Column 9 shows the inner circumbinary stability radius for the object and column 10 gives the shift for the circumbinary stability radius. Finally column 11 provides the reference for orbital parameters used in this paper.

Table 6 shows the cases where all criteria are satisfied together, i.e. objects where the intersection of habitability at periastron and apoastron is not empty. For the objects in this Table we can observe some habitability zone well defined at periastron and apoastron at the same time and also inside of the stability zone given by equations of section 3. In circumbinary cases the shift was taken into account.

In this section three particular cases are considered in order to show how the approach is implemented.

**HIP 1995**

HIP 1995 has a semimajor axis of \( a = 0.54 \text{ AU} \) with an eccentricity \( e = 0.33 \), stellar masses are \( M_{\star 1} = 1.13 M_\odot \) and \( M_{\star 2} = 0.45 M_\odot \). We have included habitable zones at periastron and apoastron (tables 3 and 4), this two separate calculations will restrict the effective habitable zone, which is located just in a circumbinary position. At Periastron we have \( R_{\text{CB}}^{\odot}(\text{inner}) = 1.49 \text{ AU} \), \( R_{\text{CB}}^{\odot}(\text{outer}) = 2.22 \), and at apoastron \( R_{\text{CB}}^{\odot}(\text{inner}) = 1.59 \text{ AU} \), \( R_{\text{CB}}^{\odot}(\text{outer}) = 2.2 \). The dynamical stability is given by the minimum radius of the circumbinary stable zone, following equation (12) this starts at \( R_{CB} = 1.66 \text{ AU} \). As an additional restriction, the shift should be considered, its value in this case is important because it change the viable zone defined under our approach, \( R_{\text{shift}} = -0.11 \text{ AU} \). Figure 12 shows all of these estimations, black (semi) dots are the stars located at periastron while (semi) dots in gray show them at apoastron. Gray disks are the habitable zones, calculated for both cases. Dark gray provides the intersection of the BHZ, the effective habitable zone for the binary. Dashed blue circle is the minimum dynamically stable circumbinary orbit, and the red one is the same but with the shift considered, this is the inner border of the viable stable orbit. Taken in to account all of these criteria is how we decide where is located the completely viable BHZ.

**HIP 80346**

This is a particular case, in this object we can found an effective habitability within the dynamical stability zone just around the secondary star. Semimajor axes of this binary is \( a = 2.07 \text{ AU} \), eccentricity \( e = 0.67 \), nevertheless stellar masses are very small, \( M_{\star 1} = 0.5 M_\odot \) and \( M_{\star 2} = 0.13 \). The main restriction to habitability is because the eccentricity of the binary. The dynamical stability region is given by equation (11) by using this relation we obtain the maximum stable orbit radius around each star, \( R_{\text{CB}}^{\odot} = 0.18 \text{ AU} \) and \( R_{\text{CB}}^{\odot} = 0.1 \text{ AU} \). Figure 13 shows both stars at periastron, the gray disks are the habitable zones, where the darker gray allows to see the habitable zone with the value at apoastron considered. Red circle around each star provides the maximum radius for dynamical stable orbits. We can observe that for the primary star habitable zone is out of dynamical stability, but in the secondary we can observe habitability within stable zone. Figure 14 shows a zoom for the secondary star of this object.

**HIP 76852**

HIP 76852, is a very particular case because we can not find a well defined circular habitable disk, nevertheless a habitable circumbinary zone is defined. Figure 15 shows this case (in units of the separation at periastron), black dots are primary (left) and secondary (right) stars located at periastron, interior dashed line is the flux isoplete that define the inner habitable zone, the exterior dashed line is the same but for the outer boundary. The inner red circle is what we have defined as the minimum circumscribe circle to the
Habitable Zones with Stable Orbits for Planets around Binary Systems

5 CONCLUSIONS

In this work we have constructed a straightforward formulation to calculate regions for habitable planets in binary stellar systems. To this purpose, we search for two general restrictions assuming in principle Earth-like planets: a) the planet must be located in a region of orbital stability (and approximately circular orbit), and b) the planet is located at a position, such as it reaches the correct host star energy, to permit the existence of liquid water on its surface (7). Some other particular restrictions, as the ones proper of the intrinsic characteristics of the planet for example, can readily be addressed to this formulation as multiplicative factors.

We have defined three zones where the binary star provides the necessary energy for habitability: (I) the zone around each star, (II) the zone around the hole binary or (II) in a mixture of this two zones. In this work, we consider a “habitable environment”, the intersection of one of these zones and the allowed dynamical zone for stable orbits.

Taking into account both restrictions, from a binary sample of main sequence stars, with known orbital parameters of the solar neighborhood (51), we have selected 25 candidates (50 % of our original sample), as plausible candidates to host habitable planets. We present this table together with three particular and interesting examples in detail: HIP 1995, HIP 80346 and HIP 76852.

We find, from our sample of candidates, that none allows planets inside the BHZ defined by the case II (circumbinary discs). This is because in all cases, the system allows habitability too close to the binary, where the stability restriction becomes very important, making impossible for all cases in our sample, to host a planet there. Although a greater sample is necessary to produce a final conclusion on the solar neighborhood, this small first sample is useful to statistically elucidate the possibilities of finding habitability on binaries of the solar neighborhood, and the possibilities for circumbinary discs seem reduced.

Software to compute numerically the size of habitable zones for binary systems is available from the authors.

We acknowledge financial support from UNAM/DGAPA through grant IN114114.

REFERENCES

Abt, H.A. 1983, Annual Review of Astronomy & Astrophysics, 21, 343
Arnold, V.I. 1984, Mathematical Methods of Classical Mechanics. Springer, Berlin, P.271
Bains, W. 2004, Astrobiology, 4, 137
Bonavita, M. & Desidera, S., A&A, 2007, 468, 721-729
Cakirli, O.; İbanoglu, C.; Bilir, S.; Sipahi, E. 2009, Monthly Notices of the Royal Astronomical Society, Vol. 395, pp. 1649
Chauvin, G., Beust, H., Lagrange, A.-M., & Eggenberger, A. 2011, Astronomy & Astrophysics, 528, A8
Correia, A. C. M., Udry, S., Mayor, M., et al. 2005, Astronomy & Astrophysics, 440, 751
CoxArthur N. 2000, Allen’s Astrophysical Quantities, Fourth Edition, Springer
Cuntz, 2013, arXiv 1303.6645
Desidera, S. & Barbieri M. 2007, A&A, 462, 345
Doyle, L.R., Billingham, J., Devincenzi, D.L. 1998, Acta Astronautica, 42, 599
Doyle, L.R., Carter, J. A., Fabrycky, D. C., et al. 2011, Science, 333, 1602
Drake, F.D. 1961, Monthly Notices of the Royal Astronomical Society, 14, 40
Dumusque, X., Pepe, F., Lovis, C., et al. 2012, Nature, 491, 207
Duquennoy, A., & Mayor, M. 1991, Astronomy & Astrophysics, 248, 485
Eggleton, P. P. 1983, Astrophysical Journal, 268, 368
Fischer, D. A., & Marcy, G. W. 1992, Astrophysical Journal, 396, 178
Hart, M.H. 1979, Icarus, 37, 351
Hale, A. 1996, in Doyle, L.R., ed, Circumstellar Habitable Zones, Travis House Pub., p. 143
Haghighipour, N. 2010, Astrophysics and Space Science Library, 366
Haghighipour, N., Dvorak, R., & Pilat-Lohinger, E. 2010, in: Planets in Binary Star Systems, Ed. Haghighipour, N. (Springer, New York)
| HIP | Alter name | Case | $R_{\text{P1}}^{\text{inner}}$ | $R_{\text{P1}}^{\text{outer}}$ | $R_{\text{P2}}^{\text{inner}}$ | $R_{\text{P2}}^{\text{outer}}$ | $R_{\text{P3}}^{\text{inner}}$ | $R_{\text{P3}}^{\text{outer}}$ |
|-----|------------|------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 101 | V821 Cas   | 3    | 3.00            | 3.00            | 3.00            | 3.00            | 3.00            | 3.00            |
| 1349| HD 1273    | 3    | 1.50            | 1.50            | 1.50            | 1.50            | 1.50            | 1.50            |
| 1955| HD 2070    | 3    | 1.00            | 1.00            | 1.00            | 1.00            | 1.00            | 1.00            |
| 2941| ADS520     | 1    | 0.50            | 0.50            | 0.50            | 0.50            | 0.50            | 0.50            |
| 5842| HD 7693    | 1    | 0.80            | 0.80            | 0.80            | 0.80            | 0.80            | 0.80            |
| 7078| HD 9021    | 3    | 1.20            | 1.20            | 1.20            | 1.20            | 1.20            | 1.20            |
| 7751| HD 10360   | 1    | 0.60            | 0.60            | 0.60            | 0.60            | 0.60            | 0.60            |
| 7918| HD 10307   | 1    | 0.70            | 0.70            | 0.70            | 0.70            | 0.70            | 0.70            |
| 8903| HD 11636   | 3    | 1.30            | 1.30            | 1.30            | 1.30            | 1.30            | 1.30            |
| 11231| HD 15064  | 3    | 1.20            | 1.20            | 1.20            | 1.20            | 1.20            | 1.20            |
| 12062| HD 15862  | 3    | 1.40            | 1.40            | 1.40            | 1.40            | 1.40            | 1.40            |
| 12153| HD 16234  | 3    | 1.50            | 1.50            | 1.50            | 1.50            | 1.50            | 1.50            |
| 12623| HD 16739  | 3    | 2.00            | 2.00            | 2.00            | 2.00            | 2.00            | 2.00            |
| 14954| HD 19994  | 1    | 1.90            | 1.90            | 1.90            | 1.90            | 1.90            | 1.90            |
| 18512| HD 24916  | 1    | 0.15            | 0.15            | 0.15            | 0.15            | 0.15            | 0.15            |
| 20087| HD 27176  | 2    | 3.50            | 3.50            | 3.50            | 3.50            | 3.50            | 3.50            |
| 20935| HD 28394  | 3    | 1.20            | 1.20            | 1.20            | 1.20            | 1.20            | 1.20            |

Table 3. Habitability zones at Periastron. Columns are: (1) HIP name, (2) Alternative name (some cases), (3) HZ case described in section 2.1.2, (4) Inner HZ for primary star, (5) Outer HZ for primary star, (6) Inner HZ for secondary star, (7) Outer HZ for secondary star, (8) Inner HZ for binary zone and (9) Outer HZ for binary zone. Note: * denote when we have defined a circumbinary habitable zone but there is no a circular shape that satisfy the minimum and maximum criteria for fluxes from both stars.
| HIP      | Alter name | Case | $R_{\text{HZ}}^\text{inner}$ (AU) | $R_{\text{HZ}}^\text{outer}$ (AU) | $R_{\text{HZ}}^\text{inner}$ (AU) | $R_{\text{HZ}}^\text{outer}$ (AU) | $R_{\text{HZ}}^\text{inner}$ (AU) | $R_{\text{HZ}}^\text{outer}$ (AU) |
|----------|------------|------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| 1349     | HD 1273    | 3    | 1.16                              | 1.82                              | 0.50                              | 0.79                              | 1.76                              | 1.53                              |
| 1955     | HD 2070    | 3    | -                                 | -                                 | -                                 | -                                 | 1.59                              | 2.20                              |
| 2941     | ADS520     | 3    | 0.55                              | 0.95                              | 0.55                              | 0.95                              | -                                 | -                                 |
| 5842     | HD 7693    | 3    | 0.87                              | 1.50                              | 0.78                              | 1.34                              | -                                 | -                                 |
| 7078     | HD 9021    | 3    | -                                 | -                                 | -                                 | -                                 | 1.91                              | 2.67                              |
| 7751     | HD 10360   | 3    | 0.66                              | 1.13                              | 0.63                              | 1.08                              | -                                 | -                                 |
| 7918     | HD 10307   | 1    | 0.71                              | 1.22                              | 0.02                              | 0.04                              | -                                 | -                                 |
| 8903     | HD 11636   | 3    | -                                 | -                                 | -                                 | -                                 | 5.01                              | 7.66                              |
| 11231    | HD 15064   | 3    | -                                 | -                                 | -                                 | -                                 | 1.48                              | 2.00                              |
| 12062    | HD 15862   | 3    | 1.00                              | 1.70                              | 0.25                              | 0.47                              | 2.00                              | 1.09                              |
| 12153    | HD 16234   | 3    | -                                 | -                                 | -                                 | -                                 | 129.76                            | 219.82                            |
| 12623    | HD 16739   | 3    | -                                 | -                                 | -                                 | -                                 | 3.09                              | 4.03                              |
| 14954    | HD 19994   | 1    | 1.92                              | 3.30                              | 0.15                              | 0.26                              | -                                 | -                                 |
| 18512    | HD 24916   | 1    | 0.15                              | 0.25                              | 0.04                              | 0.06                              | -                                 | -                                 |
| 20087    | HD 27176   | 2    | 3.24                              | 5.50                              | 1.10                              | 2.00                              | 6.40                              | 3.69                              |
| 20935    | HD 28394   | 3    | -                                 | -                                 | -                                 | -                                 | 2.17                              | 3.21                              |
| 24419    | HD 34101   | 3    | 0.89                              | 1.53                              | 0.06                              | 0.15                              | 1.60                              | 1.21                              |
| 33451    | HD 51825   | 3    | 2.72                              | 4.67                              | 1.73                              | 3.02                              | -                                 | -                                 |
| 34164    | HD 53424   | 3    | -                                 | -                                 | -                                 | -                                 | 2.11                              | 1.99                              |
| 39893    |            | 3    | 1.02                              | 1.71                              | 0.37                              | 0.67                              | 1.76                              | 1.31                              |
| 56809    | HD 10177   | 1    | 3.86                              | 6.63                              | 1.95                              | 3.35                              | -                                 | -                                 |
| 63406    | HD 112914  | 2    | 0.75                              | 1.28                              | 0.07                              | 0.14                              | -                                 | -                                 |
| 67275    | HD 120136  | 1    | 1.92                              | 3.30                              | 0.19                              | 0.33                              | -                                 | -                                 |
| 72848    | HD 131511  | 3    | -                                 | -                                 | -                                 | -                                 | 1.21                              | 1.52                              |
| 73440    | HD 15064   | 3    | 1.15                              | 1.97                              | 0.06                              | 0.46                              | 1.38                              | 1.79                              |
| 75379    | HD 137502  | 3    | -                                 | -                                 | -                                 | -                                 | 2.24                              | 2.77                              |
| 76852    | HD 140159  | 3    | 4.43                              | 7.34                              | 4.35                              | 7.21                              | 11.25                             | 6.64                              |
| 79101    | HD 145389  | 3    | -                                 | -                                 | -                                 | -                                 | 12.53                             | 18.46                             |
| 80346    |            | 3    | 0.29                              | 0.50                              | 0.02                              | 0.04                              | -                                 | -                                 |
| 80866    | HD 147584  | 3    | -                                 | -                                 | -                                 | -                                 | 1.23                              | 1.90                              |
| 82817    | HD 152771  | 1    | 0.36                              | 0.62                              | 0.14                              | 0.24                              | -                                 | -                                 |
| 82860    | HD 153597  | 3    | -                                 | -                                 | -                                 | -                                 | 1.63                              | 2.42                              |
| 84720    | HD 156274  | 3    | 0.69                              | 1.19                              | 0.26                              | 0.44                              | -                                 | -                                 |
| 84949    | HD 157482  | 3    | -                                 | -                                 | -                                 | -                                 | 9.28                              | 10.38                             |
| 86400    | HD 160346  | 3    | -                                 | -                                 | -                                 | -                                 | 0.76                              | 0.96                              |
| 86722    | HD 161198  | 3    | 0.97                              | 1.66                              | 0.14                              | 0.25                              | -                                 | -                                 |
| 87895    | HD 163840  | 3    | 1.11                              | 1.86                              | 0.58                              | 1.01                              | 2.34                              | 1.31                              |
| 91768    | HD 173739  | 1    | 0.18                              | 0.31                              | 0.14                              | 0.24                              | -                                 | -                                 |
| 93017    | ADS 11871  | 3    | 2.82                              | 4.87                              | 2.60                              | 4.49                              | -                                 | -                                 |
| 95575    | HD 183255  | 3    | -                                 | -                                 | -                                 | -                                 | 0.92                              | 1.07                              |
| 95802    | HD 181602  | 3    | -                                 | -                                 | -                                 | -                                 | 2.37                              | 3.25                              |
| 99965    | HD 193216  | 3    | -                                 | -                                 | -                                 | -                                 | 1.38                              | 1.38                              |
| 109176   | HD 210203  | 3    | -                                 | -                                 | -                                 | -                                 | 1.83                              | 2.99                              |
| 111170   | HD 213429  | 3    | -                                 | -                                 | -                                 | -                                 | 2.21                              | 1.95                              |
| 113718   | HD 217580  | 3    | 0.64                              | 1.11                              | 0.04                              | 0.09                              | -                                 | -                                 |
| 116310   | HD 221673  | 1    | 4.05                              | 6.97                              | 4.05                              | 6.97                              | -                                 | -                                 |
| 116727   | HD 222404  | 1    | 2.62                              | 4.50                              | 0.19                              | 0.32                              | -                                 | -                                 |

Table 4. Habitability zones at Apoastron. Columns are: (1) HIP name, (2) Alternative name (some cases), (3) HZ case described in section 2.1.2, (4) Inner HZ for primary star, (5) Outer HZ for primary star, (6) Inner HZ for secondary star, (7) Outer HZ for secondary star, (8) Inner HZ for binary zone and (9) Outer HZ for binary zone. Note: * denote when we have defined a circumbinary habitable zone but there is no a circular shape that satisfy the minimum and maximum criteria for fluxes from both stars.
| HIP | Alter. name | a     | e   | $m_1^*$ | $m_2^*$ | $r_{1*}^2$ | $r_{2*}^2$ | $r_{1\odot}$ | $r_{2\odot}$ | $t_{shift}$ | ref  |
|-----|-------------|-------|-----|---------|---------|------------|------------|-------------|-------------|-------------|------|
| 76852 | HD 140159   | 12.4  | 0.15 | 2.0    | 1.98    | 2.74       | 2.69       | 34.96       | -0.02       | E           |      |
| 79101 | HD 145389   | 2.24  | 0.47 | 3.47   | 1.31    | 0.33       | 0.21       | 7.23        | -0.68       | C           |      |
| 80346 |              | 2.07  | 0.67 | 0.5    | 0.13    | 0.18       | 0.1        | 6.98        | -1.04       | C           |      |
| 80686 | HD 147584   | 0.12  | 0.06 | 1.05   | 0.37    | 0.04       | 0.02       | 0.3         | -0.01       | C           |      |
| 82817 | HD 152771   | 1.38  | 0.05 | 0.56   | 0.33    | 0.08       | 0.05       | 0.96        | -0.05       | E           |      |
| 82860 | HD 153597   | 0.33  | 0.21 | 1.18   | 0.52    | 0.08       | 0.05       | 0.96        | -0.05       | E           |      |
| 84720 | HD 156274   | 91.65 | 0.78 | 0.79   | 0.47    | 3.43       | 3.41       | 321.18      | -24.55      | D           |      |
| 84949 | HD 157482   | 4.87  | 0.67 | 2.62   | 1.15    | 0.29       | 0.42       | 16.6        | -1.73       | E           |      |
| 86400 | HD 160346   | 0.39  | 0.23 | 0.72   | 0.39    | 0.08       | 0.06       | 1.15        | -0.05       | C           |      |
| 86722 | HD 161198   | 3.97  | 0.94 | 0.94   | 0.34    | 0.04       | 0.03       | 14.21       | -2.18       | E           |      |
| 87895 | HD 163840   | 2.14  | 0.41 | 0.99   | 0.68    | 0.32       | 0.27       | 6.84        | -0.25       | C           |      |
| 91768 | HD 173379   | 49.51 | 0.53 | 0.39   | 0.34    | 0.54       | 5.1        | 164.2       | -2.67       | G           |      |
| 93017 | ADS 11871   | 22.96 | 0.25 | 1.65   | 1.58    | 4.34       | 4.26       | 68.77       | -0.21       | A           |      |
| 95028 | HD 181602   | 0.85  | 0.37 | 1.4    | 0.5     | 0.15       | 0.1        | 2.65        | -0.22       | C           |      |
| 95575 | HD 183255   | 0.62  | 0.15 | 0.78   | 0.38    | 0.15       | 0.11       | 1.74        | -0.06       | C           |      |
| 98001 | HD 188753   | 11.65 | 0.47 | 1.3    | 1.11    | 1.48       | 1.38       | 37.98       | -0.66       | E           |      |
| 99965 | HD 193216   | 1.24  | 0.08 | 0.88   | 0.56    | 0.32       | 0.26       | 3.26        | -0.05       | C           |      |
| 109176| HD 210027   | 0.12  | 0    | 1.25   | 0.8    | 0.03       | 0.03       | 0.22        | 0.00        | C           |      |
| 111170| HD 213429   | 1.74  | 0.38 | 1.08   | 0.7    | 0.28       | 0.23       | 5.5         | -0.22       | C           |      |
| 113718| HD 217580   | 1.16  | 0.54 | 0.76   | 0.18    | 0.15       | 0.08       | 3.78        | -0.51       | C           |      |
| 116310| HD 221673   | 9.5   | 0.32 | 2      | 2      | 15.7       | 15.7       | 294.14      | 0.00        | H           |      |
| 116727| HD 222404   | 18.5  | 0.36 | 1.59   | 0.4    | 3.55       | 1.9        | 57.04       | -5.72       | F           |      |
| 12072 |             | 0.22  | 0.16 | 0.69   | 0.2    | 0.06       | 0.03       | 0.63        | -0.03       | I           |      |

Table 5. Orbitlal parameters and stability radii. Columns are: (1) HIP name, (2) Alternative name (some cases), (3) Semi-major axis, (4) eccentricity, (5) Mass of the primary star, (6) Mass of the secondary star, (7) Outer stable circumstellar radius for primary star, (8) Outer stable radius for secondary star, (9) Inner stable radius for secondary star, (10) References about the orbitlal parameters. References are: A=Holman & Wiegert (1999), B=Cakirli et al. (2009), C=Jancart et al. (2005), D=Bonavita & Desidera (2007), E=Martin et al. (1998), F=Desidera & Barbieri (2007), G=Strigachev & Lampens (2004), H=Muterspaugh et al. (2010) and I=Doyle et al. (2011).

---

Pierrehumbert, R., Gaidos, E., Astrophys. J. 2011, 734, L13
Pichardo, Barbara; Sparke, Linda S.; Aguilar, Luis A. 2005, Monthly Notices of the Royal Astronomical Society, 359, 521
Pichardo, Barbara; Sparke, Linda S.; Aguilar, Luis A. 2008, Monthly Notices of the Royal Astronomical Society, 391, 815
Queloz, D., Mayor, M., Webster, L., et al. 2000, Astronomy & Astrophysics, 354, 99
Schwamb, M. E., Orosz, J. A., Carter, J. A., et al. 2013, Astro-physical Journal, 768, 127
Seager, S. 2013, Exoplanet Habitability, Science 340, 577
D. J. Stevenson, 1999, Nature 400, 32
Strigachev, A. & Lampens, P. A&A, 2004, 422, 1023-1029
Welsh, W. F., Orosz, J. A., Carter, J. A., et al. 2012, Nature, 481, 475
| HIP    | Alter. Name | case | $R_{\text{inner}}^1$ AU | $R_{\text{outer}}^1$ AU | $R_{\text{inner}}^2$ AU | $R_{\text{outer}}^2$ AU | $R_{\text{inner}}^{**}$ AU | $R_{\text{outer}}^{**}$ AU |
|--------|-------------|------|---------------------------|---------------------------|-------------------------|-------------------------|-----------------------------|-----------------------------|
| –      | V821 Cas    | 3    | -                         | -                         | -                       | 5.04                    | 8.55                        |                             |
| 1953   | HD 2070     | 3    | -                         | -                         | -                       | 1.77                    | 2.20                        |                             |
| 2941   | ADS520      | 1    | 0.55                      | 0.95                      | 0.55                    | 0.95                    | -                           | -                           |
| 5842   | HD 7693     | 1    | 0.87                      | 1.50                      | 0.78                    | 1.34                    | -                           | -                           |
| 7078   | HD 9021     | 3    | -                         | -                         | -                       | 2.06                    | 2.67                        |                             |
| 7751   | HD 10360    | 1    | 0.66                      | 1.13                      | 0.63                    | 1.08                    | -                           | -                           |
| 7918   | HD 10307    | 1    | 0.71                      | 1.22                      | 0.03                    | 0.04                    | -                           | -                           |
| 8903   | HD 11636    | 3    | -                         | -                         | -                       | 5.01                    | 7.66                        |                             |
| 12153  | HD 16234    | 3    | -                         | -                         | -                       | 128.82                  | 219.85                      |                             |
| 14994  | HD 19994    | 1    | 1.92                      | 3.30                      | 0.15                    | 0.25                    | -                           | -                           |
| 18512  | HD 24916    | 1    | 0.15                      | 0.25                      | 0.04                    | 0.06                    | -                           | -                           |
| 56809  | HD 101177   | 1    | 3.86                      | 6.63                      | 1.95                    | 3.34                    | -                           | -                           |
| 67275  | HD 120136   | 1    | 1.92                      | 3.30                      | 0.19                    | 0.33                    | 0                           | -                           |
| 80346  |             | 1    | -                         | -                         | 0.03                    | 0.04                    | -                           | -                           |
| 80686  | HD 147584   | 3    | -                         | -                         | 1.23                    | 1.90                    |                             |                             |
| 82817  | HD 152771   | 1    | 0.36                      | 0.38                      | 0.14                    | 0.24                    | -                           | -                           |
| 82860  | HD 153597   | 3    | -                         | -                         | -                       | 1.63                    | 2.42                        |                             |
| 84720  | HD 156274   | 1    | 0.69                      | 1.19                      | 0.26                    | 0.44                    | -                           | -                           |
| 91768  | HD 173739   | 1    | 0.18                      | 0.31                      | 0.14                    | 0.24                    | -                           | -                           |
| 93017  | ADS 11871   | 1    | 2.86                      | 4.34                      | 2.64                    | 4.26                    | -                           | -                           |
| 95028  | HD 181602   | 3    | -                         | -                         | -                       | 2.87                    | 3.25                        |                             |
| 109176 | HD 210027   | 3    | -                         | -                         | -                       | 1.83                    | 2.99                        |                             |
| 116310 | HD 221673   | 1    | 4.06                      | 6.97                      | 4.06                    | 6.97                    | -                           | -                           |
| 116727 | HD 222404   | 1    | 2.62                      | 4.50                      | 0.20                    | 0.32                    | -                           | -                           |
| Kepler16|             | 3    | -                         | -                         | -                       | 0.06                    | 0.85                        |                             |

Table 6. Habitable binary systems with orbital stability. Columns are: (1) HIP name, (2) Alternative name (some cases), (3) Case of HZ introduced in section 2.1.2, (4) Maximum of inner radii at Apoastron and Periastron for the primary star intersected with the corresponding stability zone, (5) Minimum of outer radii at Apoastron and Periastron for the primary star intersected with the corresponding stability zone, (6) Maximum of inner radii at Apoastron and Periastron for the secondary star intersected with the corresponding stability zone, (7) Minimum of outer radii at Apoastron and Periastron for the secondary star intersected with the corresponding stability zone, (8) Maximum of inner radii at Apoastron and Periastron for the circumbinary zone intersected with the corresponding stability zone, (9) Minimum of outer radii at Apoastron and Periastron for the circumbinary zone intersected with the corresponding stability zone. Corrections because of the shift were taken into account.

A. Zsom, S. Seager, J. de Wit, 2013, [http://arxiv.org/abs/1304.3714](http://arxiv.org/abs/1304.3714)

Zucker, S., Mazeh, T., Santos, N. C., Udry, S., & Mayor, M. 2004, *Astronomy & Astrophysics*, 426, 695