Regions of Dynamical Stability for Discs and Planets in Binary Stars of the Solar Neighborhood

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ABSTRACT
Using the results of Pichardo et al. (2005,2008), we determine regions of dynamical stability where planets (or discs in general) could survive in stable orbits around binary stellar systems. We produce this study for 161 binary stars in the Solar neighborhood with known orbital parameters. Additionally, we constructed numerically the discs (invariant loops) around five binary systems with known orbital parameters and with confirmed planets: HIP 10138, HIP 4954, HIP 67275, HIP 116727 and Kepler 16, as a test to the approximation of Pichardo et al. (2005,2008). In each single case, the reported position of the planets lay within our calculated stability regions. This study intends to provide a guide in the search for planets around binary systems with well known orbital parameters, since our method defines precise limits for the stable regions, where discs may have established and planets formed.

Key words: circumstellar matter, discs – binary: stars, Solar Neighborhood, exoplanets.

1 INTRODUCTION

It is known that most low-mass main-sequence stars are members of binary or multiple systems (Duquennoy & Mayor 1991; Fisher & Marcy 1992), and in particular in the Solar Neighborhood, the fraction goes up to \(\sim 78\%\) (Abt 1983). This suggests that binary formation is the primary branch of the star formation process (Mathieu 1994).

Significant advances in high-angular-resolution infrared imaging technology have enabled large surveys of young binary stars on a variety of star-forming regions (Mathieu et al. 1992, 1994). In addition, right after the discovery of the first extrasolar planetary system around a pulsar (Wolszczan & Frail 1992), and particularly after the first extrasolar planet discovered around a main sequence star (Mayor & Queloz 1995; Marcy & Butler 1998), observational activity was greatly stimulated. More recently, advances in observational techniques and instrumentation, such as the HST (WFPC2 & NICMOS) imaging (Padgett et al. 1997, 1999; Reid et al. 2001; Borucki et al. 2010), submillimeter imaging (Smith et al. 2000), optical and infrared long-baseline interferometry (Quirrenbach 2001a,b), millimeter and sub-millimeter interferometry (Launhardt et al. 2000, Launhardt 2001, Guilloteau 2001), adaptive optics (Simon et al. 1999; Close 2001), spatial astrometry (Söderhjelm 1999; Quist & Lindegren 2000, 2001), and microlensing (Alcock et al. 2001; Dong-Wook et al. 2008; Rattenbury 2009), are also available in binary studies. Thanks to all this new technology and observational work, we have now the possibility to study and understand better the physics of binary systems and the surrounding discs built during the formation stage.

In the recent past, several planets in binary or multiple star systems have been discovered (Correia 2008; Deeg et al. 2008; Desidera & Barbieri 2007; Fischer et al. 2008; Raghavan 2006; Konacki 2005; Mugrauer et al. 2005; Eggenberger et al. 2004; Sigurdsson et al. 2003; Udry et al. 2002; Sigurdsson & Phinney 1993; Lyne 1988, etc.). Both suspected of formed in situ, or acquired by dynamical processes (Pfahl & Muterspaugh 2006). For a review of observational techniques see Muterspaugh et al. (2010). In addition, several recently discovered circumstellar discs where planets are assumed to be formed, lie around close binaries (Wright et al. 2011; Prato & Weinberger 2010; Desidera & Barbieri 2007; Doyle et al. 2011; Queloz et al. 2000; Hatzes et al. 2003). In these cases the presence of a companion star should have a very strong influence on both discs and planets. From the several hundreds of extrasolar planets confirmed so far (see http://exoplanet.eu, http://planetquest.jpl.nasa.gov, www.exoplanets.org) to be around main sequence stars, about 10\% are known to reside in binary systems with a wide range of orbital separations. In almost all cases, the planet orbits in S-type configurations...
(Dvorak 1986), while the second star acts as a perturber to the planetary system. A circumbinary planet (P-type orbit) has recently also been detected in Kepler 16 (Doyle et al. 2011). This has motivated the search for stable periodic orbits around binary systems where planets (and discs in general) can settle down in a stable configuration. Most theoretical studies have focused on binaries in near-circular orbits around binary systems where planets (and discs in general) can settle down in a stable configuration. Most theoretical studies have focused on binaries in near-circular orbits (Hénon 1970; Lubow & Shu 1975; Paczyński 1977; Papaloizou & Pringle 1977; Rudak & Paczyński 1981; Bonell & Bastien 1992; Bate 1997; Bate & Bonnell 1997). Even very precise analytical methods to approximate periodic orbits in circular binaries are available (Nagel & Pichardo 2008).

Due to the lack of conservation of the Jacobi integral, the case of eccentric binaries is qualitatively more complicated. Artymowicz & Lubow (1994) and Pichardo et al. (2005, 2008, hereafter PSA1 and PSA2) calculate the extent of zones in phase space available for stable, non self-intersecting orbits around each star and around the whole system. In this study we use the results of PSA1 and PSA2, to calculate stable regions for planets or discs in binary systems in the Solar Neighborhood with known orbital parameters such as, mass ratio, eccentricity and semimajor axis. Although the existence of stable zones, as the ones we are calculating here, is a necessary, but not a sufficient condition to the existence of planets (or discs in general), if any stable material (planets, gas, etc.), exists in a given system, irrespective of their formation mechanism, they would be necessarily located within the limits of the stable zones. In this direction, a fruitful line of investigation is the intersection between phase space available zones for the long term evolution of planetary systems and habitable regions allowed by the binary system (Haghighipour et al. 2007; Haghighipour et al. 2010).

We present a table with the compilation of all the binaries in the Solar Neighborhood with known orbital parameters from different sources. In the same table are presented the results for our calculated circumsolar and circumbinary stable zones around each binary system. This paper is organized as follows. In Section 2, we explain briefly the method employed to calculate regions of stable non self-intersecting orbits around binary stars. The binary star sample is presented in Section 3. Results, including stable regions of orbital stability for circumsolar and circumbinary planetary discs (and discs in general), and an application to observations of five binaries with observed planets, are given in Section 4. In Section 5 we present our conclusions.

2 THE METHOD

In the simpler case of circular binary orbits, the potential is time-independent in the co-rotating frame and thus the Jacobi energy is conserved. This allows the existence of closed orbits that, when stable, spawn the orbital structure of the system (Carpintero & Aguilar 1998). In the general case of binaries in eccentric orbits, the problem is more complex, as now the potential is time-dependent. However, we can exploit the fact that the time-dependency is strictly periodic.

A time-periodic potential in 2-D can be casted as a 3-D system with an autonomous Hamiltonian, with the addition of time and the original Hamiltonian as two extra dimensions in phase space. Regular orbits will lie on 3-D manifolds and be multiple periodic with three frequencies, one of which is given by the binary orbital frequency. If we take snapshots at a fixed binary phase, the projections of a regular orbit will lie on a 2-D manifold. If the orbit has an additional isolating integral of motion, this projection will now lie on a 1-D manifold: an invariant loop (Maciejewski & Sparke 1997, 2000).

Stable invariant loops represent the generalization to periodically time-varying potentials of stable periodic orbits in steady potentials. PSA1 and PSA2, implemented a numerical method to find them. The equations of motion are solved in an inertial reference frame with Cartesian coordinates with the origin at the binary barycenter. An ensemble of test particles is launched when the binary star is at periastron, and from the line that joins both stars at that moment, to search for invariant loops. A more detailed explanation of the method and a study of the phase space in binary systems is in those references. In this work we employ the formulae from PSA1 (Eq. 6) and PSA2 (Eq. 6). These relations provide the maximum radius of circumsolar stable zones and the inner radius of the circumbinary stable zone, in terms of the mass ratio \( q = m_2/(m_1 + m_2) \), where \( m_1 \) and \( m_2 \) are the masses of the primary and secondary stars, respectively, and the eccentricity \( e = \sqrt{1 - b^2/a^2} \), where \( a \) and \( b \) are the semimajor and semiminor axes of the binary orbit. The radius of the outer limit of the circumbinary stable zones from PSA1, is given by,

\[
R_i = R_{i,Egg} \times \left[ 0.733(1 - e)^{1.20} q^{0.07} \right],
\]

and a similar study in PSA2 but for the circumbinary region, gives a relation for the inner radius,

\[
R_{CB}(e, q) \approx 1.93 a (1 + 1.01 e^{0.32}) [q(1 - q)]^{0.043}.
\]

In these relations \( R_{i,Egg} \) is the approximation of Eggleton to the maximum radius of a circle circumscribed within the Roche lobe (Eggleton 1983):

\[
R_{i,Egg}/a = \frac{0.49q_i^{2/3}}{0.6q_i^{2/3} + ln(1 + q_i^{1/3})},
\]

and

\[
q_1 = m_1/m_2 = \frac{1 - q}{q} \quad \text{and} \quad q_2 = m_2/m_1 = \frac{q}{1 - q}.
\]

In Figure 1 we present a schematic figure of the geometry of the system. We show in this figure some of the variables involved in the problem.

We must emphasize that the regions of stable orbits we report here, are the regions where these invariant loops exist, and furthermore, we restrict ourselves only to non self-intersecting orbits, where gas could settle and planets may form. It is in this sense that the term "stable region" should be understood in this work. Using these formulæ and restriction, we have calculated circumbinary and circumbinary radii for our sample with a total of 161 binary systems in the solar neighborhood with known orbital parameters.
3 THE SAMPLE

The previous equations require, besides the stellar mass ratio, the semimajor axis and orbital eccentricity for each binary system, two parameters that are difficult to determine observationally. There is a diversity of methods that have been used to estimate them. Our sample is a compilation from different sources (Jancart et al. 2005; Martin et al. 1998; Strigachev & Lampens 2004; Bonavita & Desidera 2007; Holman & Wiegert 1999; Mason et al. 1999; Latham et al. 2002; Balera et al. 2006; Cakirli et al. 2009; Milone et al. 2005; Díaz et al. 2007; Konacki et al. 2010; Desidera & Barbieri 2007; Doyle et al. 2011). We include all binaries with an estimation of these parameters within 100 pc from the Sun (currently 161 systems).

In Table 4 we present our sample. Columns 1 and 2, are the name of the systems in the Hipparcos catalogue and an alternate name, if it exists. Columns 3 to 6 are our input data: the semimajor axis, orbital eccentricity and stellar masses as reported in the references listed in column 10. Columns 7 to 9 list our results: the circumprimary, circumstellar, and circumbinary boundaries of the stable regions. In the circumstellar cases, the value is the radius of the outer boundary. In the circumbinary, is the radius of the inner boundary. All lengths are given in AU and masses in solar masses. Finally, the last column is a schematic figure that gives the relative sizes and positions of the stable zones (see Figure 1). For instance, for BD -8° 4352 (9th entry in the table) the circumstellar regions are symmetric and cover a good fraction of the inner hole of the circumbinary region, this is is due to the low eccentricity of the system and its high q (=0.5). In contrast, the binary called Gamma Vir (6th entry in the table), present circumstellar regions slightly asymmetric, due to the small mass difference between the stars, and quite narrow, due to its high eccentricity.

4 RESULTS

The presence of a stellar companion, particularly in an eccentric orbit, severely curtails the size and shape of the stable zones. While a single star has circular stable orbits at all radii (neglecting finite stellar size and tidal distortion effects), the presence of a stellar companion severely curtails the region where stable, non-self intersecting orbits may exist, both in extent and, to a lesser extent, shape.

It is unclear at present the way in which these effects impose restrictions in the process of star formation. What is clear is that the effect is in the sense of inhibiting, rather than promote it.

From the observational side, the statistics of the observed systems suggests that binarity does indeed has an effect on planetary masses and orbits (Eggenberger et al. 2004), even restricting terrestrial planet formation for binary pertiastron smaller than 5 AU affecting discs to within ~1 AU of the primary star (Quintana et al. 2007, Quintana & Lissauer 2010).

The goal of this study is to determine the extent of circumstellar and circumbinary regions of stable, non-self intersecting orbits, as plausible regions where planets could have formed and may exist. It could also indicate possible regions of planetary formation.

Figure 2 shows the binary semimajor axes vs. the orbital eccentricity of our entire sample, split in mass ratio intervals. As it is already known, the region of small semimajor axes and high eccentricities is depleted, i.e. very close binaries, tidally locked in general, have eccentricities close to zero (Duquennoy & Mayor 1991). A large percentage (about 60%) of binaries in the sample have low eccentricities (e ≤ 0.5), small semimajor axes (a ≤ 50 AU) and large mass ratios (q ≥ 0.4), as shown in the histograms in Figure 2. Consequently (as seen in Figure 3), circumstellar stable regions in this sample have small radii (~2 AU), with both stable regions (circumprimary and circumsecondary) in most systems having similar size. On the other hand, the majority of circumbinary gaps have radii smaller that ~50 AU.
Figure 2. Binary semimajor axes (AU) vs eccentricities of our sample. The mass ratio is indicated with various colors and symbols, as shown in the upper left corner.

Figure 3. Histograms (from top to bottom): Eccentricity, semimajor axis and mass ratios, for all systems in our sample.

Figure 4. Histograms (from top to bottom): Circumprimary, circumsecondary and circumbinary radii, for all systems in our sample.
| Object | Alter. name | $a$ (AU) | $e$ | $M_1$ (M$_\odot$) | $M_2$ (M$_\odot$) | $R_{ce1}$ (AU) | $R_{ce2}$ (AU) | $R_{cr}$ (AU) | Ref | Scheme |
|--------|-------------|---------|-----|----------------|----------------|----------------|----------------|----------------|-----|--------|
| –      | HD 10361   | 52.2    | 0.53| 0.77           | 0.75           | 5.61           | 5.54           | 173.15         | 4   | 1      |
| –      | HD 145958A | 124     | 0.39| 0.9            | 0.89           | 18.17          | 18.08          | 393.95         | 4   | 1      |
| –      | HD 145958B | 124     | 0.39| 0.89           | 0.9            | 18.17          | 18.08          | 393.95         | 4   | 1      |
| –      | HD 146362  | 130     | 0.76| 2.19           | 1.12           | 6.98           | 5.14           | 452.9          | 4   | 1      |
| –      | ε Cet      | 1.57    | 0.27| 1.3            | 1.3            | 0.28           | 0.28           | 4.75           | 5   | 1      |
| –      | γ Vir      | 37.84   | 0.88| 0.94           | 0.9            | 0.78           | 0.78           | 135.53         | 5   | 1      |
| –      | α Com      | 12.49   | 0.5 | 1.43           | 1.37           | 1.45           | 1.42           | 41.08          | 5   | 1      |
| –      | ε CrB      | 13.98   | 0.28| 0.79           | 0.78           | 2.51           | 2.49           | 42.43          | 5   | 1      |
| –      | BD -8° 4352| 1.35    | 0.05| 0.42           | 0.42           | 0.33           | 0.33           | 3.41           | 5   | 1      |
| –      | BD 45° 2505| 4.58    | 0.73| 0.29           | 0.29           | 0.25           | 0.25           | 15.93          | 5   | 1      |
| –      | δ Equ      | 4.73    | 0.42| 1.66           | 1.59           | 0.66           | 0.64           | 15.18          | 5   | 1      |
| –      | Kpr 37     | 9.67    | 0.15| 1.2            | 0.89           | 2.26           | 1.97           | 27.23          | 5   | 1      |
| –      | 99 Her     | 16.39   | 0.74| 0.89           | 0.52           | 0.98           | 0.77           | 56.97          | 5   | 1      |
| –      | 9 Pup      | 10.00   | 0.69| 0.98           | 0.87           | 0.67           | 0.63           | 34.49          | 5   | 1      |
| –      | α CMa      | 19.89   | 0.59| 2.11           | 1.04           | 2.12           | 1.54           | 66.70          | 5   | 1      |
| –      | α Cen      | 23.57   | 0.52| 1.12           | 0.95           | 2.71           | 2.52           | 77.86          | 5   | 1      |
| –      | ξ Boo      | 33.14   | 0.51| 0.86           | 0.73           | 3.85           | 3.58           | 109.35         | 5   | 1      |
| –      | G9-42      | 0.44    | 0.81| 0.77           | 0.04           | 0.02           | 0.01           | 1.45           | 7   | 1      |
| –      | G62-30     | 0.79    | 0.59| 0.68           | 0.04           | 0.1            | 0.03           | 2.49           | 7   | 1      |
| –      | G165-22    | 0.1     | 0.08| 0.82           | 0.07           | 0.03           | 0.01           | 0.25           | 7   | 1      |
| –      | G65-52     | 0.48    | 0.26| 0.62           | 0.04           | 0.12           | 0.04           | 1.36           | 7   | 1      |
| –      | G178-27    | 0.33    | 0.43| 0.68           | 0.05           | 0.06           | 0.02           | 0.1            | 7   | 1      |
| –      | G15-6      | 0.73    | 0.45| 0.67           | 0.06           | 0.13           | 0.04           | 2.25           | 7   | 1      |
| –      | G66-65     | 0.61    | 0.9 | 0.7            | 0.04           | 0.01           | 0              | 2.05           | 7   | 1      |
| –      | G141-8     | 0.8     | 0.58| 0.77           | 0.02           | 0.11           | 0.02           | 2.43           | 7   | 1      |
| Object HIP | Alter. name | $a$ (AU) | $e$ | $M_1$ (M$\odot$) | $M_2$ (M$\odot$) | $R_{ce1}$ (AU) | $R_{ce2}$ (AU) | $R_{AB}$ (AU) | Ref | Scheme |
|------------|-------------|---------|-----|----------------|----------------|---------------|---------------|---------------|-----|---------|
| –          | G18-35      | 4.48    | 0.37| 0.75           | 0.07           | 0.93          | 0.32          | 13.44         | 7   |         |
| –          | V821 Cas    | 0.044   | 0.13| 2.046          | 1.626          | 0.01          | 0.01          | 0.12          | 10  |         |
| –          | SV Cam      | 0.016   | 0   | 0.862          | 0.646          | 0.0045        | 0.004         | 0.03          | 11  |         |
| –          | BS Dra      | 0.060   | 0   | 1.294          | 1.276          | 0.02          | 0.016         | 0.11          | 11  |         |
| 473        | HD 38       | 73.01   | 0.22| 0.76           | 0.74           | 14.41         | 14.24         | 215.35        | 3   |         |
| 1349       | HD 1273     | 1.25    | 0.57| 0.98           | 0.55           | 0.13          | 0.1           | 4.18          | 1   |         |
| 1955       | HD 2070     | 0.54    | 0.33| 1.13           | 0.48           | 0.1           | 0.07          | 1.66          | 1   |         |
| 2237       | HD 2475     | 7.08    | 0   | 1.56           | 1.24           | 1.96          | 1.76          | 12.87         | 2   |         |
| 2552       | HD 3196     | 51.3    | 0.77| 1.71           | 1.14           | 0.25          | 0.21          | 17.96         | 2   |         |
| 2941       | ADS520      | 9.57    | 0.22| 0.7            | 0.7            | 1.87          | 1.87          | 28.23         | 5   |         |
| 3821       | HD 4614     | 72      | 0.49| 0.99           | 0.51           | 9.54          | 7.05          | 235.07        | 4   |         |
| 3850       | HD 4747     | 6.7     | 0.64| 0.82           | 0.04           | 0.73          | 0.19          | 21.21         | 4   |         |
| 5531       | HD 7693     | 5.00    | 0.72| 1.17           | 1.16           | 0.29          | 0.29          | 17.36         | 8   |         |
| 5842       | HD 9021     | 0.64    | 0.31| 1.21           | 0.7            | 0.12          | 0.09          | 1.97          | 1   |         |
| 7078       | HD 10360    | 52.2    | 0.53| 0.77           | 0.75           | 5.61          | 5.54          | 173.15        | 4   |         |
| 7918       | HD 10307    | 7.1     | 0.42| 0.8            | 0.14           | 1.26          | 0.57          | 22.13         | 2   |         |
| 8903       | HD 11636    | 0.63    | 0.88| 1.86           | 1.05           | 0.01          | 0.01          | 2.25          | 1   |         |
| 8903       | HD 11636    | 0.66    | 0.9 | 2.07           | 1.28           | 0.01          | 0.01          | 2.37          | 2   |         |
| 48904      |             | 0.027   | 0.01| 0.365          | 0.348          | 0.007         | 0.006         | 0.06          | 9   |         |
| 9480       | WDS 02019+7054 | 22.5  | 0.39| 1.92           | 1.19           | 3.59          | 2.88          | 71.31         | 6   |         |
| 10138      | HD 13445    | 18.4    | 0.4 | 0.77           | 0.49           | 2.86          | 2.33          | 58.53         | 13  |         |
| 10321      | HD 13507    | 4.3     | 0.14| 1              | 0.05           | 1.34          | 0.36          | 11.18         | 4   |         |
| 11231      | HD 15064    | 0.64    | 0.29| 1.01           | 0.68           | 0.12          | 0.1           | 1.95          | 1   |         |
| Object HIP | Alter. name | $a$ (AU) | $e$ | $M_1$ (M$_\odot$) | $M_2$ (M$_\odot$) | $R_{ce1}$ (AU) | $R_{ce2}$ (AU) | $R_{cb}$ (AU) | Ref | Scheme |
|-----------|-------------|---------|----|------------------|------------------|----------------|----------------|----------------|-----|---------|
| 12062     | HD 15862    | 2.04    | 0.26 | 0.95            | 0.44             | 0.43           | 0.3            | 6.11           | 1   |         |
| 12114     | HD 16160    | 15      | 0.75 | 0.76            | 0.09             | 1.01           | 0.39           | 50.26          | 4   |         |
| 12153     | HD 16234    | 4.22    | 0.88 | 11              | 9.41             | 0.09           | 0.08           | 15.11          | 2   |         |
| 12623     | HD 16739    | 1.27    | 0.66 | 1.13            | 1.39             | 0.1            | 0.09           | 4.35           | 2   |         |
| 12777     | HD 16895    | 249.5   | 0.13 | 1.24            | 0.43             | 66.5           | 41.09          | 684.25         | 4   |         |
| 13769     | HD 18445    | 1.06    | 0.56 | 0.78            | 0.18             | 0.13           | 0.07           | 3.47           | 4   |         |
| **14954** | **HD 19994**| **120** | **0.26** | **1.35** | **0.35** | **27.34** | **14.83** | **354.86** | **13** |         |
| 18512     | HD 24916    | 174.55  | 0    | 0.35            | 0.17             | 52.36          | 37.68          | 315.65         | 3   |         |
| 19206     | HD 27176    | 9.290   | 0.69 | 0.960           | 0.790            | 0.64           | 0.58           | 32.1           | 8   |         |
| 20087     | HD 27176    | 7.05    | 0.17 | 1.76            | 0.95             | 1.66           | 1.26           | 20.08          | 2   |         |
| 20935     | HD 28394    | 0.99    | 0.24 | 1.13            | 1.11             | 0.19           | 0.19           | 2.95           | 1   |         |
| 22429     | HD 30339    | 0.13    | 0.25 | 1.39            | 0.07             | 0.03           | 0.01           | 0.36           | 4   |         |
| 23395     | WDS 05017+2640 | 10.28 | 0.33 | 1               | 0.72             | 1.79           | 1.54           | 31.9           | 6   |         |
| 23835     | HD 32923    | 2.86    | 0.9  | 1.11            | 1.03             | 0.05           | 0.05           | 10.28          | 4   |         |
| 24419     | HD 34101    | 1.75    | 0.08 | 0.9            | 0.21             | 0.52           | 0.27           | 4.52           | 1   |         |
| 25662     | HD 35956    | 2.6     | 0.62 | 0.98            | 0.18             | 0.28           | 0.13           | 8.58           | 4   |         |
| 27913     | HD 39587    | 5.9     | 0.45 | 1.05            | 0.14             | 1.01           | 0.41           | 18.41          | 4   |         |
| 29860     | HD 43587    | 11.6    | 0.8  | 1.06            | 0.34             | 0.54           | 0.32           | 40.39          | 4   |         |
| 33451     | HD 51825    | 9.3     | 0.43 | 1.61            | 1.26             | 1.31           | 1.17           | 29.93          | 2   |         |
| 34164     | HD 53424    | 1.7     | 0.27 | 1.09            | 1.09             | 0.66           | 0.27           | 5.13           | 1   |         |
| 38657     | HD 64468    | 0.56    | 0.26 | 0.81            | 0.14             | 0.13           | 0.06           | 1.64           | 4   |         |
| 39064     | HD 65430    | 4       | 0.32 | 0.83            | 0.06             | 0.92           | 0.29           | 11.66          | 4   |         |
| 39893     | HD 65430    | 1.81    | 0.21 | 0.95            | 0.52             | 0.4            | 0.31           | 5.29           | 1   |         |
| 44248     | HD 76943    | 10.51   | 0.1  | 1.53            | 0.92             | 2.69           | 2.13           | 28.27          | 2   |         |
| 44892     | HD 78418    | 0.184   | 0.2  | 1.173           | 1.011            | 0.04           | 0.04           | 0.53           | 12  |         |
| Object HIP | Alter. name | $a$ (AU) | $e$ | $M_1$ (M$_\odot$) | $M_2$ (M$_\odot$) | $R_{ce1}$ (AU) | $R_{ce2}$ (AU) | $R_{cb}$ (AU) | Ref | Scheme |
|------------|-------------|----------|-----|------------------|------------------|----------------|----------------|---------------|-----|---------|
| 45571      | HD 80671    | 4.22     | 0.51| 3.66             | 3.66             | 0.47           | 0.47           | 13.92         | 2   |         |
| 52940      | HI52940     | 2.6      | 0.37| 1.12             | 0.12             | 0.53           | 0.2            | 7.84          | 4   |         |
| 54204      | WDS 11053-2718 | 6.04 | 0.35| 1.93             | 1.93             | 0.95           | 0.95           | 18.91         | 6   |         |
| 55016      | HD 97907    | 6.87     | 0.42| 2.62             | 2.32             | 0.97           | 0.92           | 22.05         | 2   |         |
| 56809      | HD 101177   | 240.39   | 0.05| 1.95             | 1.36             | 63.9           | 54.21          | 605.53        | 3   |         |
| 60129      | HD 107259   | 10.48    | 0.08| 6.01             | 0.67             | 3.37           | 1.26           | 26.45         | 2   |         |
| 63406      | HD 112914   | 1.59     | 0.33| 0.82             | 0.23             | 0.32           | 0.18           | 4.86          | 1   |         |
| 65026      | WDS 13198+4747 | 14.36 | 0.23| 0.66             | 0.58             | 2.85           | 2.68           | 42.58         | 6   |         |
| 65343      | HD 116495   | 39.65    | 0.84| 0.61             | 0.58             | 1.17           | 1.15           | 140.96        | 3   |         |
| 66077      | 111.11      | 51.51    | 0   | 0.39             | 0.35             | 13.91          | 13.24          | 93.65         | 3   |         |
| 66492      |             | 46.59    | 0.61| 0.54             | 0.39             | 4.23           | 3.65           | 157.58        | 3   |         |
| 66640      | WDS 13396+1044 | 10.7  | 0.55| 1.24             | 1.19             | 1.09           | 1.07           | 35.68         | 6   |         |
| 67275      | HD 120136   | 245      | 0.91| 1.35             | 0.4              | 4.38           | 2.52           | 868.91        | 13  |         |
| 67422      | HD 120476   | 33.2     | 0.45| 0.76             | 0.75             | 4.3            | 4.27           | 107.59        | 3   |         |
| 67422      | HD 120476   | 33.15    | 0.44| 0.83             | 0.76             | 4.45           | 4.27           | 107.08        | 4   |         |
| 68682      | HD 122742   | 5.46     | 0.55| 1.11             | 0.55             | 0.63           | 0.45           | 18.11         | 2   |         |
| 68682      | HD 122742   | 5.3     | 0.48| 0.92             | 0.54             | 0.7            | 0.55           | 17.28         | 4   |         |
| 69226      | HD 123999   | 0.124    | 0.19| 1.411            | 1.368            | 0.026          | 0.025          | 0.359         | 12  |         |
| 71094      |             | 13.98    | 0.16| 1.89             | 1.16             | 3.28           | 2.62           | 39.6          | 2   |         |
| 71681      | HD 128621   | 22.76    | 0.51| 1.12             | 0.89             | 2.67           | 2.4            | 75.04         | 4   |         |
| 71683      | HD 128620   | 22.76    | 0.51| 1.12             | 0.89             | 2.67           | 2.4            | 75.04         | 4   |         |
| 71729      | HD 129132   | 8.28     | 0.4 | 3.34             | 3.29             | 1.19           | 1.18           | 26.4          | 2   |         |
| 72569      | HD 131156   | 32.8     | 0.51| 0.92             | 0.79             | 3.8            | 3.54           | 108.17        | 4   |         |
| 72848      | HD 131511   | 0.53     | 0.51| 0.79             | 0.45             | 0.07           | 0.05           | 1.74          | 1   |         |
| 72848      | HD 131511   | 0.52     | 0.51| 0.93             | 0.45             | 0.07           | 0.05           | 1.71          | 4   |         |

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| Object HIP | Alter. name | $a$ (AU) | $e$ | $M_1$ ($M_\odot$) | $M_2$ ($M_\odot$) | $R_{ce1}$ (AU) | $R_{ce2}$ (AU) | $R_{cb}$ (AU) | Ref | Scheme | $*_1$ | $*_2$ |
|------------|-------------|----------|-----|-----------------|-----------------|----------------|----------------|----------------|-----|--------|-------|-------|
| 73440      | HD 133621   | 1.25     | 0.22| 1.03            | 0.15            | 0.32           | 0.14           | 3.56           | 1   |        |       |       |
| 74392      | WDS 15123+1947 | 14.93   | 0.25| 3.54            | 2.51            | 2.98           | 2.55           | 44.69          | 6   |        |       |       |
| 75312      | WDS 15232+3018 | 16.15   | 0.26| 1.26            | 1.18            | 3.02           | 2.93           | 48.64          | 6   |        |       |       |
| 75379      | HD 137502   | 0.91     | 0.68| 1.26            | 0.68            | 0.07           | 0.05           | 3.12           | 1   |        |       |       |
| 76382      | ADS9716     | 19.15    | 0.59| 1.14            | 1.14            | 1.73           | 1.73           | 64.54          | 5   |        |       |       |
| 76852      | HD 140159   | 12.4     | 0.15| 2               | 1.98            | 2.7            | 2.69           | 34.96          | 2   |        |       |       |
| 77152      | HD 140913   | 0.55     | 0.54| 1.17            | 0.04            | 0.08           | 0.02           | 1.67           | 4   |        |       |       |
| 78727      | WDS 16044+1122 | 15.64  | 0.71| 0.92            | 0.92            | 0.94           | 0.94           | 54.18          | 6   |        |       |       |
| 79101      | HD 145389   | 2.24     | 0.47| 3.47            | 1.31            | 0.33           | 0.21           | 7.23           | 1   |        |       |       |
| 80046      | HD 145784   | 0.12     | 0.06| 1.05            | 0.37            | 0.04           | 0.02           | 0.3            | 1   |        |       |       |
| 81126      | HD 149630   | 6.33     | 0.53| 3.04            | 1.5             | 0.77           | 0.55           | 20.89          | 2   |        |       |       |
| 82817      | HD 152771   | 1.38     | 0.05| 0.33            | 0.56            | 0.38           | 0.3            | 3.47           | 2   |        |       |       |
| 82860      | HD 153597   | 0.33     | 0.21| 1.18            | 0.52            | 0.08           | 0.05           | 0.96           | 1   |        |       |       |
| 83895      | HD 155763   | 7.09     | 0   | 5.94            | 3.65            | 2.05           | 1.64           | 12.86          | 2   |        |       |       |
| 84140      | HD 155876   | 5.01     | 0.75| 0.38            | 0.37            | 0.25           | 0.25           | 17.5           | 2   |        |       |       |
| 84720      | HD 156274   | 91.65    | 0.78| 0.79            | 0.47            | 4.33           | 3.41           | 321.18         | 4   |        |       |       |
| 84949      | HD 157482   | 4.87     | 0.67| 1.15            | 2.62            | 0.29           | 0.42           | 16.6           | 2   |        |       |       |
| 85141      | HD 157498   | 9.29     | 0.58| 1.79            | 1.75            | 0.87           | 0.86           | 31.22          | 2   |        |       |       |
| 86201      | HD 160922   | 0.082    | 0   | 1.460           | 1.180           | 0.02           | 0.011          | 0.143          | 12  |        |       |       |
| 86221      | WDS 17370+2753 | 9       | 0.21| 0.64            | 0.63            | 1.8            | 1.79           | 26.4           | 6   |        |       |       |
| 86400      | HD 1360346  | 0.39     | 0.23| 0.72            | 0.39            | 0.08           | 0.06           | 1.15           | 1   |        |       |       |
| 86722      | HD 161198   | 3.97     | 0.94| 0.94            | 0.34            | 0.04           | 0.03           | 14.21          | 2   |        |       |       |
| 86974      | HD 161797   | 22       | 0.32| 1.15            | 0.13            | 4.92           | 1.85           | 65.17          | 4   |        |       |       |
| 87895      | HD 163840   | 2.14     | 0.41| 0.99            | 0.68            | 0.32           | 0.27           | 6.84           | 1   |        |       |       |
| Object HIP | Alter. name | $a$ (AU) | $e$ | $M_1$ ($M_\odot$) | $M_2$ ($M_\odot$) | $R_{cc1}$ (AU) | $R_{cc2}$ (AU) | $R_{cb}$ (AU) | Ref | Scheme |
|------------|-------------|----------|-----|-------------------|-------------------|----------------|----------------|----------------|-----|---------|
| 89937      | HD 170153   | 1.05     | 0.41| 1.18              | 0.77              | 0.16           | 0.13           | 3.35           | 1   |         |
| 90355      | HD 169822   | 0.84     | 0.48| 0.91              | 0.3               | 0.12           | 0.07           | 2.71           | 4   |         |
| 91768      | HD 173739   | 49.51    | 0.53| 0.39              | 0.34              | 5.43           | 5.1            | 164.2          | 3   |         |
| 92418      | HD 174457   | 1.9      | 0.23| 1.07              | 0.06              | 0.52           | 0.14           | 5.26           | 4   |         |
| 92835      | HP Dra      | 0.123    | 0.06| 1.102             | 1.099             | 0.03           | 0.03           | 0.31           | 11  |         |
| 93017      | ADS 11871   | 22.96    | 0.25| 1.65              | 1.58              | 4.34           | 4.26           | 68.77          | 5   |         |
| 93506      | WDS 19026+2953 | 13.36  | 0.2 | 2.97              | 2.4               | 2.81           | 2.55           | 38.93          | 6   |         |
| 93574      | HD 175986   | 9.01     | 0.39| 1.89              | 1.65              | 1.35           | 1.27           | 28.62          | 2   |         |
| 95028      | HD 181602   | 0.85     | 0.37| 1.4               | 0.5               | 0.15           | 0.1            | 2.65           | 1   |         |
| 95575      | HD 183255   | 0.62     | 0.15| 0.78              | 0.38              | 0.15           | 0.11           | 1.74           | 1   |         |
| 95995      | HD 184467   | 1.45     | 0.37| 1.22              | 0.46              | 0.26           | 0.17           | 4.53           | 2   |         |
| 96302      | HD 184759   | 4.68     | 0.82| 3.34              | 1.59              | 0.18           | 0.13           | 16.48          | 2   |         |
| 96471      | HD 184860   | 1.4      | 0.67| 0.77              | 0.03              | 0.14           | 0.03           | 4.42           | 4   |         |
| 98001      | HD 188753   | 11.65    | 0.47| 1.3               | 1.11              | 1.48           | 1.38           | 37.98          | 2   |         |
| 99965      | HD 193216   | 1.24     | 0.08| 0.88              | 0.56              | 0.32           | 0.26           | 3.26           | 1   |         |
| 103641     | HD 200077   | 0.587    | 0.66| 1.186             | 0.941             | 0.04           | 0.04           | 2.01           | 12  |         |
| 104019     | WDS 21044+1951 | 12.86 | 0.39| 1.67              | 1                 | 2.06           | 1.63           | 40.74          | 6   |         |
| 105969     | HD 204613   | 2.06     | 0.13| 1.01              | 0.49              | 0.52           | 0.38           | 5.68           | 1   |         |
| 107354     | HD 206901   | 8.24     | 0.31| 1.56              | 2.6               | 1.53           | 1.21           | 25.32          | 2   |         |
| 108473     | HD 208776   | 4.2      | 0.27| 1.14              | 0.51              | 0.87           | 0.61           | 12.62          | 4   |         |
| 109176     | HD 210027   | 0.12     | 0            | 1.25              | 0.8               | 0.03           | 0.03           | 0.22           | 1   |         |
| 110893     | HD 239960   | 9.51     | 0.42| 0.28              | 0.15              | 1.46           | 1.1            | 30.4           | 3   |         |
| 110893     | ADS15972    | 9.53     | 0.41| 0.27              | 0.17              | 1.51           | 1.20           | 30.41          | 5   |         |
| 111170     | HD 213429   | 1.74     | 0.38| 1.08              | 0.7               | 0.28           | 0.23           | 5.5            | 1   |         |
| 113718     | HD 217580   | 1.16     | 0.54| 0.76              | 0.18              | 0.15           | 0.08           | 3.78           | 1   |         |
| Object     | Alter. name | a  | ε    | M1  | M2  | Rce1 | Rce2 | Rb  | Ref  | Scheme |
|------------|-------------|----|------|-----|-----|------|------|-----|------|--------|
| HIP 116310 | HD 221673   | 95 | 0.322| 2.0 | 2.0 | 15.70| 15.70| 294.14 | 16    |
| HIP 116727 | HD 222404   | 18.5| 0.36 | 1.59| 0.4 | 3.55 | 1.9  | 57.04 | 13    |
| HIP 117666 | WDS 23517+0637 | 10.2| 0.3  | 0.6 | 0.58| 1.77 | 1.74 | 31.29 | 6     |
| HIP         | Kepler 16   | 0.22| 0.16 | 0.69| 0.20| 0.06 | 0.03 | 0.63 | 14    |
| HIP         | K10848064   | 0.049| 0    | 1.2 | 0.073| 0.018| 0.005| 0.083 | 15    |
| HIP         | K08016222   | 0.065| 0.044| 1.1 | 0.086| 0.023| 0.007| 0.154 | 15    |
| HIP         | K09512641   | 0.060| 0    | 1.2 | 0.140| 0.021| 0.008| 0.105 | 15    |
| HIP         | K07254760   | 0.042| 0    | 1.2 | 0.215| 0.014| 0.007| 0.075 | 15    |
| HIP         | K05263749   | 0.055| 0    | 1.3 | 0.266| 0.018| 0.009| 0.097 | 15    |
| HIP         | K04577324   | 0.039| 0    | 1.2 | 0.241| 0.013| 0.006| 0.069 | 15    |
| HIP         | K06370196   | 0.061| 0    | 1.3 | 0.359| 0.020| 0.011| 0.108 | 15    |

(1) Jancart et al. 2005, (2) Martin et al. 1998, (3) Strigachev and Lampens 2004, (4) Bonavita and Desidera 2007, (5) Holman and Wiegert 1998, (6) Mason et al. 1999, (7) Latham et al. 2002, (8) Balega et al. 2006, (9) Diaz et al. 2007, (10) Cakirli et al. 2009, (11) Milone et al. 2005, (12) Konacki et al. 2010, (13) Desidera and Barbieri 2007, (14) Doyle et al. 2011, (15) Faigler et al. 2011, (16) Muterspaugh et al. 2010
4.1 Application to Real Systems

The perturbing effect of stellar companions lead to a widespread belief that the presence of planets in binary systems was very unlikely. Now we know that binaries can have planets, and thus should have stable regions around them where planet formation took place. Queloz et al. 2000, and Hatzes et al. 2003, discovered two giant planets in the binary systems GJ 86 and γ Cephei. Since then, binaries have become important targets in the search for extrasolar planets, particularly given their abundance.

Until now about 70 binary systems with planets have been discovered (Wright et al. 2011), but only for eight of them, orbital parameters (semimajor axis, eccentricity and mass ratio) are available (Desidera & Barbieri 2007, Doyle et al. 2011, Muterspaugh et al. 2010). Table 4 shows our prediction for the extent of the stable orbits regions for these systems (in bold type letter). In all cases, where the semimajor axis of the planet is known, the observed planet is located within the predicted stable zone. We present figures with the calculated stable regions constructed with invariant loops, for the five cases where planets are confirmed, and the values for the semimajor axis of observed planets are known.

In particular, notice the case of HD 120136, this is an open binary with a very high eccentricity, usually treated as single star for this reason. The large eccentricity results in a very narrow, circumstellar stable region. Even so, the discovered planet lies in a P-type orbit inside our predicted circumstellar stable region.

4.1.1 HIP 10138 (HD 13445 or GL 86)

This binary system is located at a distance of 10.9 ± 0.08 pc. The companion of this object, discovered by Els et al. 2001, has a semimajor axis of 18.4 AU, with an eccentricity of 0.4. The spectral type of the most massive component is K1 with a mass of 0.77 M⊙ and it is a white dwarf (Mugrauer & Neuhauser 2005). The companion has a mass of 0.49 M⊙. At the moment, one planet was found in this system with a mass of $M_p \sin i = 4.0 \, M_J$. It has a semimajor axis of 0.113 AU and an eccentricity of 0.4 (Bonavita & Desidera 2007). For this binary the calculated stable zone located around each star is $R_{ce1} = 3.06 \, AU$ around the principal component, $R_{ce2} = 2.49 \, AU$ around the companion, in both cases this radii is the outermost radii possible to have stable orbits, and $R_{cb} = 58.53 \, AU$ as the innermost radii available for circumbinary orbits.

In Figure 5 we present the circumprimary, circumsencondary and circumbinary regions of orbital stability, for planets in this case, to settle down, calculated at periastron with our method. The stellar orbits are marked in green. The known planet is orbiting the primary star in a very small orbital radius, indistinguishable in this figure.

4.1.2 HIP 14954 (HD 19994 or 94 Cet)

This binary system is located at a distance of 22.6 pc. Its semimajor axis is 120 AU and it has eccentricity of 0.26. The mass of the primary star is 1.35 M⊙ with a spectral type F8 V, the mass of the secondary star is 0.35 M⊙. The planet orbiting this object has a semimajor axis of 1.428 AU with an eccentricity of 0.30 and $M_p \sin i = 1.69 \, M_J$ (Desidera & Barbieri 2007).

In Figure 6, circumstellar, circumbinary stable regions, and planetary orbit (in red) are shown. Stellar orbits (green) are also indicated.

4.1.3 HIP 67275 (HD 120136 or τ Boo)

This system is located at 15.62 pc, and it has the largest eccentricity for the cases of binary systems with known orbital parameters, which here are semimajor axis 245 AU, eccentricity of 0.91 and masses 1.35 M⊙ for the primary and 0.4 M⊙ for the secondary component. The planet observed in this system has a semimajor axis of 0.048 AU while our approach predicts a maximum radii of 4.86 AU, the eccentricity planet is 0.023 and $M_p \sin i = 4.13$ (Desidera & Barbieri 2007).
Figure 6. Stable zones around the system HD 19994 (94 Cet). The upper panel shows the circumstellar regions, primary star to the left secondary to the right. The bottom panel shows the circumbinary region, notice the change in scale. The green curves show the stellar orbits, the system is presented at periastron. Orbital parameters: $M_1 = 1.35 \, M_\odot$, $M_2 = 0.35 \, M_\odot$, $e = 0.26$, $a = 120 \, \text{AU}$.

In Figure 7, we present the circumprimary, circumsecondary and circumbinary stable regions, for planets in this case, calculated at periastron. The stellar orbits are marked in green. The known planet is orbiting the primary star in a very small orbital radius, indistinguishable in this figure.

4.1.4 HIP 116727 (HD 222404 or Gamma Cep)

This system is located at a distance of 14.1 pc. The spectral type of the main component is K, and its mass is $1.59 M_\odot$, while the mass of the companion is $0.4 \, M_\odot$, the semimajor axis is $18.5 \, \text{AU}$ with an eccentricity of 0.36. The planet in this system has a semimajor axis of $2.14 \, \text{AU}$, with an eccentricity $0.12$ and $M_p \sin i = 1.77 \, M_J$ (Desidera & Barbieri 2007).

In Figure 8, circumstellar stable regions, circumbinary stable region (gray), and planetary orbit (in red) are shown. Stellar orbits (green) are also indicated.

4.1.5 Kepler 16

Recently it was found in this system a planet in circumbinary orbit, this the first observed of this kind (on the circumbinary disc). The primary star has a mass of $0.69 \, M_\odot$, and the companion has a mass of $0.20 \, M_\odot$, the semimajor axis is $0.22 \, \text{AU}$ with an eccentricity of 0.16 (Doyle et al. 2011). The discovered planet has a semimajor axis of $0.71 \, \text{AU}$, with an eccentricity of 0.0069 and a mass of $0.33 \, M_J$.

In Figure 9, circumstellar stable regions, circumbinary stable region, and planetary orbit (in red) are shown. Stellar orbits (green) are also indicated.
Figure 8. Stable zones around the system HD 222404 (Gamma Cep). The upper panel shows the circumstellar regions, primary star to the left secondary to the right. The bottom panel shows the circumbinary region, notice the change in scale. The green curves show the stellar orbits, the system is presented at periastron. In this case planet orbit is not close to the star, line darker (red) around the primary star shows its orbit. Orbital parameters for the star: $M_1 = 1.59 \, M_\odot$, $M_2 = 0.4 \, M_\odot$, $e = 0.36$, $a = 18.5 \, AU$.

Figure 9. Stable zones around the system Kepler 16. The upper panel shows the circumstellar regions, primary star to the left secondary to the right. The bottom panel shows the circumbinary region, notice the change in scale. The green curves show the stellar orbits, the system is presented at periastron. Orbital parameters: $M_1 = 0.69 \, M_\odot$, $M_2 = 0.20 \, M_\odot$, $e = 0.16$, $a = 0.22 \, AU$.

5 CONCLUSIONS

We have compiled a sample of binary stars with known orbital parameters (semimajor axes, eccentricities and stellar masses) of the Solar neighborhood and present some basic statistics.

We calculate on this binary stars sample the extent of regions of stable non-self intersecting orbits where planets may exist. For this purpose, we have applied the concept of “invariant loops” and used the formulae of PSA1 and PSA2. Our approximation is ballistic, thus, the application is straightforward to debris discs (planets, cometary nuclei, asteroid belts, etc.). In the case of gas discs, further physics may constraint discs sizes, however, what we are providing here are the regions where the most important orbits of the binary, i.e., the ones that represent the backbone of the dynamical system (the ones that are followed for the most of the orbits), lay. We have computed the spatial limits of these circumstellar and circumbinary zones for a sample of 161 binaries in the Solar neighborhood where orbital data is known and presented it in the form of a table where all the relevant parameters are provided.

We compare our results with observations in the 5 cases where planets have been discovered in binary systems, and where semimajor axis for the planets are provided. We find that all the planets lay down within our computed regions of stability. In particular, for HD 120136, our predicted region
of circumstellar stability is very small, and yet the discovered planet lays within it. Although confrontation with a larger database is desirable, the current statistics is fully consistent with our results, proving reliable our approach. The tool of “invariant loops” may be very helpful in the search for planets in binary systems.

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