1 Formation, Dynamical Evolution, and Habitability of Planets in Binary Star Systems

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Abstract. A survey of currently known planet-hosting stars indicates that approximately 25% of extrasolar planetary systems are within dual-star environments. Several of these systems contain stellar companions on moderately close orbits, implying that studies of the formation and dynamical evolution of giant and terrestrial planets, in and around binary star systems have now found realistic grounds. With the recent launch of the space telescope CoRoT, and the launch of NASA’s Kepler satellite in 2009, the number of such dynamically complex systems will soon increase and many more of their diverse and interesting dynamical characteristics will soon be discovered. It is therefore, both timely and necessary, to obtain a deep understanding of the history and current status of research on planets in binary star systems. This chapter will serve this purpose by reviewing the models of the formation of giant and terrestrial planets in dual-star environments, and by presenting results of the studies of their dynamical evolution and habitability, as well as the mechanisms of delivery of water and other volatiles to their terrestrial-class objects. In this chapter, the reader is presented with a comprehensive, yet relatively less technical approach to the study of planets in and around binary stars, and with discussions on the differences between dynamical characteristics of these systems and planetary systems around single stars.

1.1 Introduction

The concept of a “world with two suns” has been of interest to astronomers for many years. Many scientists tried to understand whether planets could form in binary star systems, and whether the notion of habitability, as we know it, could be extended to such environments. Although as a result of their respective works, many dynamical features of binary-planetary systems have been discovered, until recently, the subjects of their studies were, in large part, hypothetical. There was no detection of a planet in and/or around a binary system, and planet detection techniques had not advanced enough to successfully detect planets in dual-star environments.

The discovery of extrasolar planets during the past decade has, however, changed this trend. Although the candidate planet-hosting stars have been routinely chosen to be single, or within wide (>100 AU) binaries, the precision radial velocity

1 A binary-planetary system is a dual-star system that also hosts planetary bodies.
2 As shown by Norwood & Haghighipour (2002), the perturbative effect of the stellar companion on the dynamics of a planetary system around a star becomes important.
technique has been successful in detecting planets around the primaries of three moderately close (<40 AU) dual-star systems. As a result, during the past few years, the topic of planets in binaries, once again, found its way to the mainstream research and has now become a real scientific issue that demands theoretical explanations.

The first detection of a planet in a binary system was reported by Campbell, Walker & Yang in 1988. In an attempt to identify planetary objects outside our solar system, these authors measured the variations in the radial velocities of a number of stars, and reported the possibility of the presence of a Jovian-type body around the star \( \gamma \) Cephei (figure 9.1, Campbell, Walker & Yang, 1988). This star, that is a K1 IV sub-giant with a mass of 1.59 solar-masses (Fuhrmann, 2004), is the primary of a binary system with a semimajor axis of 18.5 AU and an eccentricity of 0.36 (Griffin, Carquillat, & Ginestet, 2002; Hatzes et al. 2003). The secondary of this system is an M dwarf with a mass of 0.44 solar-masses (Neuhäuser et al., 2007; Torres, 2007). Initial radial velocity measurements of \( \gamma \) Cephei implied that this star may be host to a giant planet with a probable mass of 1.7 Jupiter-masses, in an orbit with a semimajor axis of 1.94 AU (Campbell, Walker & Yang, 1988).

Unfortunately, the discovery of the first binary-planetary system, which could have also marked the detection of the first planet outside our solar system, did not withstand skepticism. In an article in 1992, Walker and his colleagues attributed their measured variations of the radial velocity of \( \gamma \) Cephei to the chromospheric

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when the binary separation is smaller than 100 AU. At the present, approximately 25% of extrasolar planetary systems detected by radial velocity technique are in binary systems with separations ranging from 250 to 6000 AU.
activities of this star, and announced that the possibility of the existence of a giant planet around \(\gamma\) Cephei may be none (\cite{Walker1992}). It took observers an additional 12 years to monitor \(\gamma\) Cephei and measure its radial velocity to arrive at the conclusion that the previously observed variations were not due to stellar activities and were in fact representative of a planetary companion (figure 9.2). It was the discovery of a giant planet in the binary system of Gl 86 (\cite{Queloz2000}), and the (re-)announcement of the detection of a giant planet in \(\gamma\) Cephei system (\cite{Hatzes2003}) that opened a new chapter in the theoretical and observational studies of extrasolar planetary systems.

The fact that giant planets exist in moderately close (<40 AU) binary systems has confronted dynamicists with many new challenges. Questions such as, how are these planets formed, can binary-planetary systems host terrestrial and/or habitable planets, how are habitable planets formed in such dynamically complex environments, and how do such planets acquire the ingredients necessary for life, are among major topics of research in this area. This chapter is devoted to review these issues and present the current status of research on the formation of planets in dual-star systems and habitability of terrestrial bodies in and around binary stars.

The chapter begins with a review of the dynamics of a planet in a binary star system. In general, prior to constructing a theory for the formation of planets, it proves useful to study whether the orbit of a planet around its host star would be stable. In a binary system, such studies are of quite importance since in these systems the perturbation of the stellar companion may dictate the possibility of the formation of planetary bodies by affecting the stability and dynamics of smaller objects.

The formation of planets in binary star systems is reviewed in the third section. Although the study of the dynamics of planets in and around binary stars dates back to approximately forty year ago, the formation of planets in these systems is an issue that is still unresolved. In spite the observational evidence that indicate majority of main and pre-main sequence stars are formed in binaries or clusters (\cite{Abt1979, Duquennoy1991, Mathieu1994, Mathieu2000, White2001}), and in spite the detection of potentially planet-forming environments in and around binary stars (figure 9.3, also see \cite{Mathieu1994, Akeson1998, Rodriguez1998, White1999, Silbert2000, Mathieu2000}), planet formation theories are still unclear in explaining how planets may form in multi-star environments. The focus of section 9.3 is on discussing the formation of giant and terrestrial planets in moderately close binary-planetary systems, and reviewing the current status of planet formation theories in this area.

The habitability of a binary system is presented in section 9.4. The notion of habitability is defined based on the habitability of Earth and life, as we know it. Such a definition requires a habitable planet to have the capability of retaining liquid water in its atmosphere and on its surface. The latter is determined by the luminosity of the central star, the size of the planet, and also the distribution of water in the protoplanetary disk from which terrestrial-class objects are formed.
Fig. 1.2. Radial velocity measurements of the primary of γ Cephei binary system. The graph on the top shows the orbital solution for the planet (solid line) and the residual velocity measurements after subtracting the contribution due to the binary companion (data points). The graph on the bottom depicts the phased residual radial velocity measurements (data points) compared to the planet orbital solution (solid line) (Hatzes et al., 2003).
In section 9.4, a review of the current status of the models of habitable planet formation in and around binary systems are presented, and their connections to

models of terrestrial planet formation and water-delivery around single stars are discussed. Finally the chapter ends by discussing the future prospects of research in the field of planets in binaries.

### 1.2 Dynamical Evolution and Stability

In general, one can consider orbital stability synonymous with the capability of an object in maintaining its orbital parameters (i.e., semimajor axis, eccentricity, and inclination) at all times. In other words, an object is stable if small variations in its orbital parameters do not progress exponentially, but instead vary sinusoidally.
Instability occurs when the perturbative forces create drastic changes in the time variations of these parameters and result in either the ejection of the object from the system (i.e., leaving the system’s gravitational field), or its collision with other bodies.

![Fig. 1.4. S-type and P-type binary-planetary systems. A and B represent the stars of the binary, and P depicts the planet.](image)

The concept of stability, as explained above, although simple, has been defined differently by different authors. A review by Szebehely in 1984 lists 50 different definitions for the stability of an object in a multi-body system (Szebehely, 1984). For instance, Harrington (1977) considered the orbit of an object stable if, while numerically integrating the object’s orbit, its semimajor axis and orbital eccentricity would not undergo secular changes. Szebehely (1980), and Szebehely & McKenzie (1981), on the other hand, considered integrals of motion and curves of zero velocity to determine the stability of a planet in and around binary stars. In this chapter, the values of the orbital eccentricity of an object and its semimajor axis are used to evaluate its stability. An object is considered stable if, for the duration of the integration of its orbit, the value of its orbital eccentricity stays below unity, it does not collide with other bodies, and does not leave the gravitational field of its host star.

The study of the stability of a planetary orbit in dual stars requires a detailed analysis of the dynamical evolution of a three-body system. Such an analysis itself is dependent upon the type of the planetary orbit. In general, a planetary-class object may have three types of orbit in and around a binary star system. Szebehely (1980) and Dvorak (1982) have divided these orbits into three different categories. As indicated by Szebehely (1980), a planet may be in an inner orbit, where it revolves around the primary star, or it may be in a satellite orbit, where it revolves around the secondary star. A planet may also be revolving the entire binary system in which case its orbit is called an outer orbit. As classified by Dvorak (1982), on the other hand, a study of the stability of resonant periodic orbits in a restricted, circular, three-body system indicates that a planet may have an S-type orbit, where it revolves around only one of the stars of the binary, or may be in a P-type orbit,
where it revolves the entire binary system (figure 9.4). A planet may also be in an L-type orbit where it librates in a stable orbit around the $L_4$ or $L_5$ Lagrangian points.

The rest of this section is devoted to a review of the studies of the stability of planets in S-type and P-type orbits. Given that in a binary star system, a planet is subject to the gravitational attraction of two massive bodies (i.e., the stars), it would be important to understand how the process of the formation of planetary objects, and the orbital dynamics of small bodies would be affected by the orbital characteristics of the binary’s stellar components. In general, except for some special cases for which analytical solutions may exist, such studies require numerical integrations of the orbits of all the bodies in the system. In the past, prior to the invention of symplectic integrators (Wisdom & Holman, 1991), which enabled dynamicists to extend the studies of the stability of planetary systems to several hundred million years, and before the development of fast computers, majority of such studies were either limited to those special cases, or were carried out numerically for only a small number of binary’s orbital period. Examples of such studies can be found in articles by Graziani & Black (1981), Black (1982), and Pendleton & Black (1983), in which the authors studied the orbital stability of a planet in and around a binary star. By numerically integrating the equations of the motion of the planet, this authors showed that, when the stars of the binary have equal masses, the orbital stability of the planet is independent of its orbital inclination (also see Harrington, 1977). Their integrations also indicate that, when the mass of one of the stellar components is comparable to the mass of Jupiter, planetary orbits with inclinations higher than $50^\circ$ tend to become unstable.

The invention of symplectic integrators, in particular routines that have been designed specifically for the purpose of integrating orbits of small bodies in dual-star systems (Chambers et al., 2002), have now enabled dynamicists to extend studies of planet formation and stability in dual-star environments to much larger timescales. In the following, the results of such studies are discussed in more detail.

### 1.2.1 Stability of S-type orbits

As mentioned above, instability occurs when the perturbative effects cause the semi-major axis and orbital eccentricity of a planet change in such a way that either the object leaves the gravitational field of the system, or it collides with another body. For a planet in an S-type orbit, the gravitational force of the secondary star is the source of these perturbations. That implies, a planet at a large distance from the secondary, i.e., in an orbit closer to its host star, may receive less perturbation from other bodies. However, when the planet is closer to the primary star, it may experience stronger perturbations from both stars.

Symplectic integrators, as they were originally developed by Wisdom & Holman (1991), are not suitable for numerically integrating the orbits of small bodies in the gravitational fields of two massive objects. These integrators have been designed to integrate the orbits of planetary or smaller objects when they revolve around only one massive central body. Recently Chambers et al. (2002) have developed a version of a symplectic integrator that is capable of integrating the motion of a small object in the gravitational fields of two stellar bodies.
the binary companion and may be able to sustain its dynamical state for a longer time (Harrington, 1977). Since the perturbative effect of the stellar companion varies with its mass, and the eccentricity and semimajor axis of the binary (which together determine the closest approach of the secondary to the planet), it is possible to estimate an upper limit for the planet’s distance to the star beyond which the orbit of the planet would be unstable. As shown by Rabl & Dvorak (1988) and Holman & Wiegert (1999), the maximum value that the semimajor axis of a planet in an S-type orbit can attain and still maintain its orbital stability is a function of the mass-ratio and orbital elements of the binary, and is given by (Rabl & Dvorak, 1988; Holman & Wiegert, 1999):

\[
a_c/a_b = (0.464 \pm 0.006) + (-0.380 \pm 0.010)\mu + (-0.631 \pm 0.034)e_b + (0.586 \pm 0.061)\mu e_b + (0.150 \pm 0.041)e_b^2 + (-0.198 \pm 0.047)\mu e_b^2 .
\] (1.1)

In this equation, \(a_c\) is critical semimajor axis, \(\mu = M_1/(M_1 + M_2)\), \(a_b\) and \(e_b\) are the semimajor axis and eccentricity of the binary, and \(M_1\) and \(M_2\) are the masses of the primary and secondary stars, respectively. The ± signs in equation (9.1) define a lower and an upper value for the critical semimajor axis \(a_c\), and set a transitional region that consists of a mix of stable and unstable systems. Such a dynamically gray
area, in which the state of a system changes from stability to instability, is known to exist in multi-body environments, and is a characteristic of any dynamical system.

Equation (9.1) is an empirical formula that has been obtained by numerically integrating the orbit of a test particle (i.e., a massless object) at different distances from the primary of a binary star (Rabl & Dvorak, 1988; Holman & Wiegert, 1999). Figure 9.5 shows this in more detail. Similar studies have been done by Moriwaki & Nakagawa (2004), and Fatuzzo et al. (2006) who obtained critical

![Graphs of the semimajor axes (left) and eccentricities (right) of the giant planet (black) and binary (green) of γ Caphei for different values of the eccentricities of the binary (Haghighipour, 2003). The mass-ratio of the binary is 0.2.](image)

semimajor axes slightly larger than given by equation (9.1).

Since the mass of a Jovian-type planet is approximately three orders of magnitude smaller than the mass of a star, such a test particle approximation yields results that not only are applicable to the stability of giant planets, but can also be used in identifying regions where smaller bodies, such as terrestrial-class objects (Quintana et al., 2002; Quintana & Lissauer, 2006; Quintana et al., 2007) and dust particles (Trilling et al., 2007), can have long term stable orbits. In a recent article, Trilling et al. (2007) utilized equation (9.1) and its stability criteria to explain the dynamics of debris disks, and the possibility of the formation and existence of planetesimals in and around 22 binary star systems. By detecting infrared excess of dust particles, these authors confirmed the presence of stable dust bands, possibly resulted from collision of planetesimals, in S-type orbits in several wide binaries.

The stability of S-type systems has been studied by many authors (Benest, 1988, 1989, 1993, 1996; Wiegert & Holman, 1997; Pilat-Lohinger & Dvorak, 2002). In applying equation (9.1) to the stability of dust particles, one has to note that this equation does not take into account the effects of non-gravitational forces such as gas-drag or radiation pressure. The motion of a dust particles can be strongly altered by the effects of these forces.
In a recent article, Haghighipour (2006) extended such studies to the dynamical stability of the Jupiter-like planet of the $\gamma$ Cephei planetary system. By numerically integrating the orbit of this object for different values of $a_b$, $e_b$ and $i_p$ (the orbital inclination of the giant planet relative to the plane of the binary), Haghighipour (2006) has shown that the orbit of this planet is stable for the values of the binary eccentricity within the range $0.2 \leq e_b \leq 0.45$. Figure 9.6 shows the results of such integrations for a coplanar system with $\mu = 0.2$.

Interesting results were obtained when the $\gamma$ Cephei system was integrated for different values of $i_p$. The results indicated that for the above-mentioned range of orbital eccentricity, the planet maintains its orbit for all values of inclination less than $40^\circ$. Figure 9.7 shows the semimajor axes and orbital eccentricities of the system for $e_b = 0.2$ and for $i_p = 5^\circ$, $10^\circ$, and $20^\circ$. For orbital inclinations larger than $40^\circ$, the system becomes unstable in a few thousand years.

**Kozai Resonance**

An interesting dynamical phenomenon that may occur in an S-type binary, and has also been observed in the numerical simulations of a few of these systems, is the Kozai resonance (Haghighipour, 2003, 2005; Verrier & Evans, 2006; Takeda & Rasio, 2006; Malmberg, Davies & Chambers, 2007). As demonstrated by Kozai (1962), in a three-body system with two massive objects and a small body (e.g., a binary-planetary system), the exchange of angular momentum between the planet and the secondary star, can cause the orbital eccentricity of the planet to reach high values at large inclinations. Averaging the equations of motion of the system over mean
anomalies, one can show that in this case, the averaged system is integrable when the ratio of distances are large (the Hill’s approximation, [Kozai 1962]). The Lagrange equations of motion in this case, indicate that, to the first order of planet’s eccentricity, the longitude of the periastron of this object, \( \omega_p \), librates around a fixed value. Figure 9.8 shows this for the giant planet of \( \gamma \) Cephei. As shown here, \( \omega_p \) librates around 90° ([Haghighipour 2003, 2005]).

In a Kozai resonance, the longitude of periastron and the orbital eccentricity of the small body \( (e_p) \) are related to its orbital inclination as ([Innanen 1997])

\[
\sin^2 \omega_p = 0.4 \csc^2 i_p, \tag{1.2}
\]

and

\[
(e_p^2)_{\text{max}} = \frac{1}{6} \left[ 1 - 5 \cos(2i_p) \right]. \tag{1.3}
\]
From equation (9.3), one can show that the Kozai resonance may occur if the orbital inclination of the small body is larger than $39.23^\circ$. For instance, as shown by Haghighipour (2003, 2005), in the system of $\gamma$ Cephei, Kozai resonance occurs at $i_p = 60^\circ$. For the minimum value of $i_p$, the maximum value of the planet’s orbital eccentricity, as given by equation (9.4), is equal to 0.764. Figure 9.8 also shows that $e_p$ stays below this limiting value at all times.

As shown by Kozai (1962) and Innanen (1997), in a Kozai resonance, the disturbing function of the system, averaged over the mean anomalies, is independent of the longitudes of ascending nodes of the small object (the planet) and the perturbing body (the stellar companion). As a result, the quantity $\sqrt{a(1 - e^2) \cos i}$ (shown as the “Reduced Delaunay Momentum” in figure 9.8) becomes a constant of motion. Since the eccentricity and inclination of the planet vary with time, the fact that the quantity above is a constant of motion implies that the time-variations of these two quantities have similar periods and, at the same time, they vary in such a way that when $i_p$ reaches its maximum, $e_p$ reaches its minimum and vice versa. Figure 9.9 shows this clearly.

![Figure 1.9. Graphs of the eccentricity and inclination of the giant planet of $\gamma$ Cephei in a Kozai Resonance (Haghighipour, 2003, 2005). As expected, these quantities have similar periodicity and are $180^\circ$ out of phase.](image)

1.2.2 Stability of P-type Orbits

Numerical simulations have also been carried out for the stability of P-type orbits in binary-planetary systems (Ziglin, 1975; Szebehely & McKenzie, 1981; Dvorak, 1984, 1986; Dvorak, Froeschlé, & Froeschlé, 1989; Kubala, Black & Szebehely; Holman & Wiegert, 1999; Broucke, 2001; Pilat-Lohinger, Funk & Dvorak, 2003; Musielak et al., 2005). Similar to S-type orbits, in order for a P-type planet to be stable, it has to be at a safe distance from the two stars so that it would be immune from their perturbative effects. That is, planets at large distances from the center of mass of a binary will have a better chance of begin stable. This distance, however, cannot be too large
because at very large distances, other astronomical effects, such as galactic perturbation, and perturbations due to passing stars, can render the orbit of a planet unstable.

To determine the critical value of the semimajor axis of a P-type planet in a stable orbit, preliminary attempts were made by Dvorak (1984), who numerically integrated the orbit of a circumbinary planet in a circular orbit around an eccentric binary system and showed that planets at distances 2-3 times the separation of the binary have stable orbits. Subsequent studies by Dvorak (1986), Dvorak, Froeschlé, & Froeschlé (1989), and Holman & Wiegert (1999) complemented Dvorak’s results of 1984 and showed that the orbit of a P-type planet will be stable as long as the semimajor axis of the planet stays larger than the critical value given by (figure 9.10)

**Fig. 1.10.** Critical semimajor axis as a function of the binary eccentricity in a P-type system (Holman & Wiegert 1999). The squares correspond to the result of stability simulations by Holman & Wiegert (1999) and the triangles represent those of Dvorak, Froeschlé, & Froeschlé (1989). The solid line corresponds to equation (9.4). As indicated by Holman & Wiegert (1999), the figure shows that at outer regions, the stability of the system fades away.
\[ a_c/a_b = (1.60 \pm 0.04) + (5.10 \pm 0.05)e_b + (4.12 \pm 0.09)\mu \\
+ (-2.22 \pm 0.11)e^2_b + (-4.27 \pm 0.17)e_b\mu + (-5.09 \pm 0.11)\mu^2 \\
+ (4.61 \pm 0.36)e^2_b\mu^2. \] (1.4)

Similar to equation (9.1), equation (9.4) represents a transitional region with a lower boundary below which the orbit of a P-type planet will be certainly unstable, and an upper boundary beyond which the orbit of the planet will be stable. The mixed zone between these two boundaries represents a region where a planet, depending on its orbital parameters, and the orbital parameters and the mass-ratio of the binary, may or may not be stable. Recently, by applying the stability criteria of equation (9.4) to their observational results, Trilling et al. (2007) have confirmed the presence of stable dust band, possibly resulted from collision of planetesimal, around close binary star systems.

A dynamically interesting feature of the stable region around the stars of a binary is the appearance of islands of instability. As shown by Holman & Wiegert (1999) islands of instability may develop beyond the inner boundary of the mixed zone, which correspond to the locations of \((n : 1)\) mean-motion resonances. The appearance of these unstable regions have been reported by several authors under various circumstances (Hénon & Gueyot, 1970; Dvorak, 1984; Rabl & Dvorak, 1988; Dvorak, Froeschlé, & Froeschlé, 1989). Extensive numerical simulations would be necessary to determine whether the overlapping of these resonances would result in stable P-type binary-planetary orbits.

1.3 Planet Formation in Binaries

Despite a wealth of articles on planets in binary star systems, the process of the formation of these objects is still poorly understood. The current theories of planet formation focus only on the formation of planets in a circumstellar disk around a single star, and their extensions to binary environments are limited to either the Sun-Jupiter system, where the focus is on the effect of Jupiter on the formation of inner planets of our solar system (Heppenheimer, 1974, 1978; Drobyshevski, 1978; Diakov & Reznikov, 1980; Whitmire et al., 1998; Kortenkamp, Wetherill & Inaba), or binaries resembling some of extrasolar planets, in which the secondary star has a mass in the brown dwarf regime (Whitmire et al., 1998). Although attempts have been made to extend such studies to binaries with comparable-mass stellar components (Marzari & Scholl, 2000; Nelson, 2000; Barbieri, Marzari & Scholl, 2002; Quintana et al., 2002; Lissauer et al., 2004), the extent of the applicability of the results of these studies has been only to hypothetical cases since, until recently, there had been no observational evidence on the existence of such binary-planetary systems.
In general, it is believed that planet formation proceeds through the following four stages (figure 9.11):

1) coagulation of dust particles and their growth to centimeter-sized objects,
2) collisional growth of centimeter-sized particles to kilometer-sized bodies (planetesimals),
3) formation of Moon- to Mars-sized protoplanets (also known as planetary embryos) through the collision and coalescence of planetesimals, and
4) collisional growth of planetary embryos to terrestrial-sized objects.

The latter is a slow process that may take a few hundred million years. During the first few million years of this process, at larger distances from the star, planetesimals and planetary embryos may form planetary cores several times more massive than Earth, and may proceed to form giant planets.

In a binary star system with a moderate to small separation, the secondary star will have significant effects on the efficiency of each of these processes. As shown by Boss (2006), a binary companion can alter the structure of a planet-forming nebula, and create regions where the densities of the gas and dust are locally enhanced (figure 9.12). Also, as shown by Artymowicz & Lubow (1994), and Pichardo, Sparke & Aguilar (2005), a stellar component on an eccentric orbit can truncate the circumprimary disk of embryos to smaller radii and remove material that may be used in the formation of terrestrial planets (figure 9.13). As a result, it used to be believed that circumstellar disks around the stars of a binary may not be massive enough to form planets. However, observations by Mathieu (1994),
Fig. 1.12. Structure of a circumprimary disk in a double star system. The masses of the primary and secondary stars are 1 and 0.09 solar-masses, respectively. The secondary star is at 50 AU at the top of the figure, and has an eccentricity of 0.5. The figure shows an area of 20 AU around the primary. The structures inside the disk have appeared after 239 years from the beginning of the simulations. The orange structure on the right edge of the graph is an artifact of numerical simulations (Boss, 2006).

Akeson, Koerner & Jensen (1998), Rodriguez et al. (1998), and Mathieu et al. (2000) have indicated that potentially planet-forming circumstellar disks can indeed exist around the stars of a binary system, implying that planet formation in binaries may be as common as around single stars (figure 9.14). Among these circumstellar disks, the two well-separated disks of the system L1551 retain equivalent of approximately 0.03 to 0.06 solar-masses of their original circumstellar materials in a region with an outer radius of ∼10 AU (figure 9.14, Rodriguez et al., 1998). The masses of these disks are comparable to the minimum solar-mass model of the primordial nebula of our solar system (Weidenschilling, 1977; Hayashi, 1981), implying that, planet formation in dual-star systems can begin and continue in the same fashion as around our Sun.

Despite the observational evidence in support of the existence of planet-forming environments in moderately close binary star systems, the perturbative effect of the binary companion may not always favor planet formation. For instance, as shown by Nelson (2000), giant planet formation cannot proceed through the disk instability mechanism (Boss, 2000) around the primary of a binary star system with separation of ∼50 AU. Also, when forming planetary embryos, as shown by Heppenheimer (1978), Whitmire et al. (1998), and Thébault et al. (2004), the perturbation of the secondary star may increase the relative velocities of planetesimals and cause...
Fig. 1.13. Disk Truncation in and around binary systems ([Artymowicz & Lubow, 1994]). The top graphs show circumstellar disk in a binary with a mass-ratio of 0.3. Note the disk truncation when the eccentricity of the binary is increased from 0 to 0.3. The bottom graphs show similar effect in a circumbinary disk. The mass-ratio is 0.3 and the binary eccentricity is 0.1. The numbers inside each graph represent the time in units of the binary period. The axes are in units of the binary semimajor axis.
Fig. 1.14. Interferometric observation of the binary system L1551 (Rodriguez et al., 1998). Two compact sources are evident in the map. The separation of the binary is 45 AU and the disk around each core extends to approximately 10 AU.

...their collisions to result in breakage and fragmentation (figure 9.15). Results of the studies by these authors suggest that planetesimal accretion will be efficient only in binaries with large separation [50 AU as indicated by Heppenheimer (1978), 26 AU as shown by Whitmire et al. (1998), and 100 AU as reported by Mayer et al. (2005)]. Finally, in a binary star system, the stellar companion may create unstable regions where the building blocks of planets will not maintain their orbits and, as a result, planet formation will be inhibited (Whitmire et al., 1998).

Interestingly, despite all these difficulties, numerical simulations have shown that it may indeed be possible to form giant and/or terrestrial planets in and around a dual-star system. Recent simulations by Boss (2006), and Mayer, Boss & Nelson (2007) indicate that Jupiter-like planets can form around the primary of a binary star system via gravitational instability in a marginally unstable circumprimary disk (figure 9.16). On the other hand, as shown by Thébault et al. (2004), the core accretion mechanism may also be able to form giant planets around the primary of a binary star. However, as the results of their simulations for planet formation in the γ Cephei system indicate, the semimajor axis of the final gas-giant planet may be smaller than its observed value.
Fig. 1.15. Graphs of the evolution of eccentricity (top) and encounter velocities (bottom) for planetesimals at the region between 0.3 and 5 AU from the primary of γ Cephei (Thébault et al., 2004). The planetesimals disk in the bottom simulation was initially at its truncated radius of 4 AU. As shown here, the perturbative effect of the secondary star increases the eccentricities and relative velocities of these objects.
In regard to the formation of terrestrial planets in binary systems, in a series of articles, Quintana and her colleagues integrated the orbits of a few hundred Moon- to Mars-sized objects and showed that terrestrial-class objects can form in and around binaries (Quintana et al., 2002; Lissauer et al., 2004; Quintana & Lissauer, 2006; Quintana et al., 2007). Figure 9.17 shows the results of some of their simulations. As shown here, depending on the mass-ratio of the binary and the initial values of its orbital parameters, in a few hundred million years, terrestrial planets can form around a close (0.01 to 0.1 AU) binary star system.

Quintana and colleagues also studied terrestrial planet formation in binaries with larger separations (Quintana et al., 2007). Figure 9.18 shows the results of their simulations for a binary with a separation of 20 AU. Similar to figure 9.17, terrestrial-type objects are formed around the primary of the binary in a few hundred million years. Statistical analysis of their results, as shown in figures 9.19, 9.20, and 9.21 indicate that, as expected in binaries with larger perihelia, where disk truncation has been smaller and more planet-forming material is available, terrestrial planet formation is efficient and the number of final terrestrial planets is large. The results of simulations by Quintana et al. (2007) also indicate that in a binary with a periastron distance larger than 10 AU, terrestrial planet formation can proceed efficiently in a region within 2 AU of the primary star. In binaries with periastra smaller than 5 AU, this region may be limited to inside 1 AU (figure 9.20).
Fig. 1.17. Terrestrial planet formation around a close binary system (Quintana & Lissauer, 2006). The binary is circular and its separation is 0.05 AU. Each star of the binary has a mass of 0.5 solar-masses. A Jupiter-like planet has also been included in the simulation. The circles represent planetary embryos and planetesimals with radii that are proportional to their physical sizes. As shown here, the perturbative effect of the outer giant planet excite the orbits of the bodies at the outer edge of the disk and causes radial mixing as well as truncation. Within the first 100 Myr, several terrestrial-class objects are formed around the binary system.

Despite the destructive role of the binary companion in increasing the relative velocities of planetesimals, which causes their collisions to result in erosion, this efficiency of terrestrial planet formation in binary systems may be attribute to the fact that the effect of the binary companion on increasing the relative velocities of planetesimals can be counterbalanced by dissipative forces such as gas-drag and dynamical friction (Marzari et al., 1997; Marzari & Scholl, 2000). The combination of the drag force of the gas and the gravitational force of the secondary star may result in the alignment of the periastra of planetesimals and increases the efficiency of their accretion by reducing their relative velocities. This is a process that is more effective when the sizes of the two colliding planetesimals are comparable and small. For colliding bodies with different sizes, depending on the size distribution of small objects, and the radius of each individual planetesimal, the process of the alignment of periastra may instead increase the relative velocities of the two objects, and cause their collisions to become eroding (figure 9.22, also see Thébault et al., 2006).
Fig. 1.18. Terrestrial planet formation around the primary of a binary star system (Quintana et al., 2007). The stars of the binary are 0.5 solar-mass with semimajor axis of 20 AU. The eccentricity of the binary is 0.75 (left column), 0.625 (middle column), and 0.5 (right column). As shown here, in each simulations, two terrestrial-type objects are formed after 100 Myr. The last row shows the results of additional simulations of the same systems, with final results showing in black, gray and white, corresponding to different runs. The differences in the final assembly of the planetary system of each simulation are results of the stochasticity of this type of numerical integrations.

Simulations of terrestrial planet formation have also been extended to binaries with larger separations (20-40 AU) that also host a giant planet (Haghighipour & Raymond, 2007). As discussed in the next section, by numerically integrating the orbits of the binary, its giant planet, and a few hundred planetary embryos, these authors have shown that it is possible to form Earth-like objects, with considerable amount of water, in the habitable zone of the primary of a moderately close binary-planetary system.
Fig. 1.19. Graphs of the final masses of the terrestrial planets formed in systems of figure 9.18. The simulations have been run for three different masses of the binary stars. The red corresponds to simulations in a binary with 0.5 solar-masses stars, the blue represents results in a binary with 1 solar-mass stars, yellow is for a binary with a 1 solar-mass primary and a 0.5 solar-masses secondary, and black represents a binary with a 0.5 solar-masses primary and a 1 solar-mass secondary. These results show that despite the disk truncation in binaries with smaller perihelia, the average masses of the final planets are not significantly altered. (Quintana et al., 2007).

Fig. 1.20. Graphs of the semimajor axis of the outermost planet of the simulations of figure 9.18. A shown here, while the outer edge of the disk is affected by the presence of the binary companion, the inner portion of the disk, where terrestrial planets are formed, stays unaffected by this object (Quintana et al., 2007).
Fig. 1.21. Number of final terrestrial-type planets formed in the binaries of figure 9.18. As expected, for a given binary mass-ratio, the number of terrestrial planets increases in systems with larger perihelia. This number also increases when the mass of the binary companion is smaller. (Quintana et al., 2007).

Fig. 1.22. Encounter velocities of planetesimals with different sizes in a binary system with semimajor axis of 10 AU, eccentricity of 0.3, and mass-ratio of 0.5 (Thébault et al., 2006). The simulations include gas-drag. The vertical line shows the time of orbital crossing. As shown here, gas-drag lowers the encounter velocities of smaller equal-size planetesimals through the periastron alignment process.
1.4 Habitability

It is widely accepted that a planet capable of developing life (as we know it), has to be able to continuously maintain liquid water on its surface and in its atmosphere. The capability of a planet in retaining water depends on its size and the processes involving its interior dynamics and atmospheric circulation. It also depends on its orbital parameters (i.e., its semimajor axis and orbital eccentricity) and the brightness of the central star at the location of the planet. While a dynamic interior and atmospheric circulation are necessary for a habitable planet to develop CO$_2$ cycle and generate greenhouse effect (which helps the planet to maintain a uniform temperature), a long-term stable orbit, at a right distance from the star, is essential to ensure that the planet will receive the amount of radiation that enables it to maintain liquid water on its surface. These seemingly unrelated characteristics of a potential habitable planet, have strong intrinsic correlations, and combined with the luminosity of the star, determine the system’s habitable zone.

The inner and outer boundaries of a habitable zone vary with the star’s luminosity and the planet’s atmospheric circulation models [see Menou & Tabachnik (2003), Jones, Underwood, & Sleep (2005), and Jones, Sleep, & Underwood (2006) for a table of distances of the inner and outer boundaries of the habitable zones of exoplanetary systems]. A conservative estimate of the habitable zone of a star can be made by assuming that its inner edge is located at a distance closer than which water on the surface of the planet evaporates due to runaway greenhouse effect, and its outer edge is at a distance where, in the absence of CO$_2$ clouds, runaway glaciation will freeze the water and creates permanent ice on the surface of the planet. As shown by Kasting, Whitmire, & Reynolds (1993), such a definition of a habitable zone results in a habitable region between 0.95 AU and 1.15 AU for the Sun (figure 9.23). This is a somewhat conservative estimate of the Sun’s habitable zone and as noted by Jones, Underwood, & Sleep (2005), the outer edge of this region may, in fact, be farther away (Forget & Pierrehumbert, 1997; Williams & Kasting, 1997; Mischna et al., 2000).

Since the notion of habitability is based on life on Earth, it is possible to calculate the location of the boundaries of the habitable zone of a star by comparing its luminosity with that of the Sun. For a star with the surface temperature $T$ and radius $R$, the luminosity $L$ is given by

$$L(R, T) = 4\pi\sigma T^4 R^2,$$

where $\sigma$ is Boltzmann constant. Using equation (9.5) and the fact that Earth is in the habitable zone of the Sun, the radial distances of the inner and outer edges of the habitable zone of a star can be obtained from (Haghighipour 2006)

$$r = \left(\frac{T}{T_\odot}\right)^2 \left(\frac{R}{R_\odot}\right) r_\odot.$$

The quantities $T_\odot$ and $R_\odot$ in equation (9.6) are the surface temperature and radius of the Sun, respectively, and $r_\odot$ represent the radial distance of Earth from the
Equation (9.6) implies that a habitable zone can be defined as a region around a star where an Earth-like planet can receive the same amount of radiation as Earth receives from the Sun, so that it can develop and maintain similar habitable conditions as those on Earth.

As mentioned above, the orbit of a potential habitable planet in the habitable zone of a star has to be stable over long durations of time. As shown in section 9.2, the stability of the orbit of a planet in a binary system is strongly affected by the orbital motion of the binary companion. In binary systems where the primary hosts other planetary bodies (e.g., giant planets), the dynamics of a habitable planet will also be affected by the gravitational perturbations of these objects. It is therefore important to determine under what conditions a terrestrial-class object will have a long-term stable orbit in the habitable zone of a binary system, prior to construction a theory for the formation of Earth-like planets in such environments.

Since a terrestrial-class planet is approximately two orders of magnitude less massive than a Jovian-type object, it will not have significant effect on the motion of the stars and the giant planets of a binary system. Therefore, as explained in sections 9.2.1 and 9.2.2, if a binary system does not contain a Jupiter-like planet, any dynamical criterion that is obtained for the stability or instability of a general planetary body, can also be applied to the dynamics of a terrestrial planet. Equation
Fig. 1.24. Graph of the lifetime of an Earth-size object in a circular orbit around the primary of γ Cephei. The habitable zone of the primary has been indicated by HZ. No planet was placed in the region between the aphelion and perihelion distances of the giant planet of the system. As shown here, only Earth-size planets close to the primary star maintain their orbits for long times (Haghighipour, 2006).

(9.1) and the stability conditions presented by figure 9.5 can be used to determine the long-term stability of an Earth-like object in a binary system.

If a binary contains giant planets, however, the situation is different. The gravitational perturbations of the latter objects will have significant effects on the motion and dynamics of terrestrial planets in the system. As shown by Haghighipour (2006), an Earth-size object, in a region between the giant planet and the primary of γ Cephei binary system, can maintain its stability only in orbits close to the primary star and outside the influence zone of the giant body. Integrating the equations of motion of a full four-body system, this author has shown that an Earth-like planet will not be able to sustain a stable orbit in the habitable zone of γ Cephei’s primary star (figure 9.24). However, it is possible for such an object to have a stable orbit when \(0.3 \leq a_T \leq 0.8\) AU, \(0^\circ \leq i_T \leq 10^\circ\), and \(e_b \leq 0.4\). Here \(a_T\) represents the semimajor axis of the terrestrial planet and \(i_T\) is its orbital inclinations with respect to the plane of the binary.

As mentioned above, the instability of an Earth-like planet in the habitable zone of γ Cephei can be attributed to the interaction between this object and the giant planet of the system. When the Earth-like planet is outside the giant planet’s influence area, the object will maintain its stability.

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5 The influence zone of a planetary object with a mass \(m_p\) around a star with a mass \(M\) is defined as the region between \(3R_H - a_p(1 - e_p)\) and \(3R_H + a_p(1 + e_p)\), where \(a_p\) is the semimajor axis of the planet, and \(R_H = a_p(m_p/3M)^{1/3}\) is its Hill radius. 
Fig. 1.25. Formation of Earth-like planets in a binary-planetary systems. The top panel shows simulations in a binary with a separation of 30 AU, eccentricity of 0.2, and stellar components of 1 solar-mass. As shown here, an Earth-like planet (1.17 Earth-masses) with a water to mass ratio of 0.00164, is formed in the habitable zone of the primary at 1.16 AU, with an eccentricity of 0.02. The bottom panel shows the formation of an Earth-like object in a binary with a solar-mass primary and a 1.5 solar-masses secondary. The separation of the binary in this case is 30 AU, the mass of the Earth-like planets is 0.95 Earth-masses and its water to mass ratio is 0.00226. The semimajor axis of this planet and its orbital eccentricity are equal to 0.99 AU and 0.07, respectively. For the sake of comparison, Sun’s habitable zone is approximately at 0.95–1.15 AU, Earth’s orbital eccentricity is 0.017, and Earth’s water to mass ratio is $\sim 0.001$ [Haghighipour & Raymond (2007)].
Fig. 1.26. Formation of Earth-like planets in different binary-planetary systems. As shown here, for a given binary mass-ratio, the delivery of water to terrestrial region becomes less efficient as the perihelion distance of the binary becomes smaller (Haghighipour & Raymond, 2007).

fluence zone (e.g., at closer distances to the primary star) it can maintain its orbit for several hundred million years. Figure 9.24 suggest that, in order for a binary-planetary system to be habitable, its habitable zone has to be outside the influence region of its giant planet. In an S-type binary-planetary system, this implies a primary with a close-in habitable region. In a recent article, Haghighipour & Raymond (2007) have studies the habitability of such a system. By considering a binary with a Sun-like primary star and a Jupiter-sized planet in a circular orbit at 5 AU, and by adopting the model of Morbidelli et al. (2000), which is based on the assumption that water-carrying objects, in the Sun’s asteroid belt, were the primary source of the delivery of water to Earth, these authors integrated the orbits of a few hundred
Fig. 1.27. The \((e_b, a_b)\) parameter-space of an equal-mass binary-planetary system. Circles correspond to binaries with initial parameters chosen from figure 9.25, in which habitable planets were formed. Triangles represent systems in which the giant planet became unstable. The numbers associated with each circle represents the mean eccentricity of the giant planet of the system at the end of the simulation. As shown here, moderately close binaries with lower eccentricities (larger perihelia) are more suitable places for the formation of habitable planets (Haghighipour & Raymond, 2007).

protoplanetary (Moon- to Mars-sized) objects, and showed that it is indeed possible to form Earth-sized planets, with substantial amount of water, in the habitable zone of the primary star (figure 9.25). As shown by these authors, the mass and orbital parameters of the secondary star play important roles in the radial mixing of protoplanetary objects and the delivery of water to the habitable zone of the primary star. The giant planet of the system also plays the important role of transferring angular momentum from the secondary star to the disk of protoplanets, and enhancing the radial mixing of these objects. As shown in figure 9.26, water delivery is less efficient in binaries with smaller perihelia since in such systems, the close approach of the binary companion to the giant planet increases its eccentricity, which in turn results in stronger interaction between this object and the disk of protoplanets, causing them to become unstable in very short time. The results of the simulations by Haghighipour & Raymond (2007) indicate that binary-planetary systems with giant planets at 5-10 AU, and binary perihelion distances of approximately 20 AU to 25 AU, will be more efficient in forming and hosting habitable planets (figure 9.27).
1.5 Future Prospects

The discovery of planets in binary star systems is one of the interesting surprises of modern astronomy. Despite the long history of the study of planets in such environments, the recent detection of planets in moderately close binaries has confronted astronomers with many new challenges. Many aspects of the formation process of these planets are still unresolved, and questions regarding their frequency and detection techniques demand more detailed investigation.

The habitability of binary systems is also an open question. Although recent simulations of the late stage of terrestrial planet formation in binary systems have indicated that water-carrying planets can form in the habitable zone of a binary-planetary system, more studies are necessary to understand how protoplanetary objects can develop and evolve in such an environment. Such studies have implications for investigating the habitability of extrasolar planets, and tie directly to several of near-future NASA missions, in particular, the space mission Kepler.

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Fig. 1.28. Artistic rendition of the view from the moon of a giant planet in a triple star system. Figure from JPL-Caltech/NASA.