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Terrestrial Planet Formation in Binary Star Systems

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Abstract.
Observations show that more than half of all main sequence stars have a stellar companion (Duquennoy & Mayor 1991). Perturbations from a companion star can disrupt the formation and long-term stability of planets. We numerically explore the final stages of terrestrial planet formation – the growth from Moon- to Mars-sized planetary embryos into planets – in a wide variety of main sequence binary star systems. We examine planetary accretion around each star in α Centauri AB, the closest binary star system to the Sun, and around individual stars of other 'wide' binary systems (with stellar separations from 5 – 40 AU). We also explore planet formation around both members of 'close' (0.05 – 0.4 AU) binary star systems. Our results are statistically compared to simulations using the same initial disk around a single Sun-like star (with and without Jupiter and Saturn included).

From 3 – 5 terrestrial planets similar to those in the Solar System formed around each star in α Cen AB in simulations that began with a disk of embryos inclined $\lesssim 30°$ to the binary orbital plane. We found that for wide and close binary star systems, the binary periastron (closest approach) and apastron (maximum stellar separation), respectively, are the most influential stellar parameters on planetary accretion. Terrestrial planets formed in Earth-like ($\sim$1 AU) orbits around individual stars in binary systems with periastron $\gtrsim$ 7 AU, and surrounding close binary stars with stellar apastrons $\lesssim$ 0.2 AU. Approximately 50 - 60% of binary star systems - from contact binaries to separations of nearly a parsec - satisfy these constraints. Given that the galaxy contains more than 100 billion star systems, a large number of systems can potentially harbor Earth-like habitable planets.

1. Introduction

More than half of all main sequence stars, and an even larger fraction of pre-main sequence stars, reside in binary/multiple star systems (Duquennoy & Mayor 1991; Mathieu et al. 2000). The presence of disk material has been indirectly observed around one or both components of some young binary star systems (Mathieu et al. 2000). Terrestrial planets and the cores of giant planets are thought to form by an accretion process from a disk of dust and gas (Safronov 1969; Lissauer 1993). A recent survey of circumstellar disks of dust grains reveals that disks around stars with a stellar companion are similar to those around single stars if the binary (projected) semimajor axis is $\gtrsim$ 10 AU.

More than 200 extrasolar planets have been detected to date, and 42 of these are giant planets on so-called 'S-type' orbits that encircle one member of a binary star system (Eggenberger & Udry 2007), including 3 with projected separations of only $\sim$20 AU. The effect of the stellar companion on the formation of these planets, however, remains uncertain. Terrestrial planets have yet to be detected in 'P-type' orbits (which encircle both components) of a main-sequence binary star system, but close binaries are not included in precise Doppler radial velocity search programs because of their complex and varying spectra. The presence of Earth-like exoplanets in main sequence single or binary star systems has yet to be determined, although the *Kepler Mission*, scheduled to launch in early 2009, has the potential to find true Earth-analogues in both single and multiple star systems[1].

We have numerically simulated the final stages of terrestrial planet formation in both S-type and P-type orbits within main sequence binary star systems using two symplectic algorithms (Chambers et al. 2002). Our numerical model and calculations of the dynamical stability regions in binary star systems are presented in §2. We discuss the results of our planetary accretion simulations in S-type orbits around each star in the α Centauri AB binary system (§3), in other wide binary star systems (§4), and in P-type orbits surrounding close binary stars (§5). We summarize our results in §6, and discuss the implications on the fraction of stars in the galaxy that can potentially harbor habitable terrestrial planets.

2. Numerical Model and Initial Conditions

We recently helped to develop two symplectic integration algorithms designed to examine planetary accretion in S-type or P-type orbits in binary star systems (Chambers et al. 2002). We first examined the stability regions in binary star systems by integrating a suite of test particles, analogous to simulations performed by Wiegert & Holman (1997). For a wide range of binary eccentricities (e_B) and stellar mass ratios (μ), the test particles were followed for 10^6 binary periods, and the outermost S-type stable orbit for wide binary stars – or the innermost P-type stable orbit for close binary stars – was determined for each set of stellar parameters. Figure 1 shows the results (interpolated with a cubic spline) for the stellar parameters that we examined in all of our our planet formation simulations.

Our planetary *accretion* simulations examine the late stages of terrestrial planet formation, in which planets form via pair-wise accretion of Moon- to Mars-sized rocky planetesimals/embryos that have already accreted from within a disk of gas and dust. We base our disk model on simulations of terrestrial planet growth around the Sun (Chambers 2001), which resulted in planetary systems similar to the Mercury-Venus-Earth-Mars system of planets. This disk is composed of 14 rocky embryos (each with 0.1 times the mass of the Earth, $M_\oplus$), and 140 planetesimals (each with 0.01 $M_\oplus$), distributed between 0.36 – 2 AU. The surface density profile is of the form $a^{-3/2}$ (where a is the semimajor axis), normalized to 8 g/cm^2 at 1 AU, which follows from models of the minimum mass solar nebula. The radius of each body is calculated assuming a material density of 3 g cm^{-3}, and are subject to gravitational perturbations from both

[1]see www.kepler.arc.nasa.gov

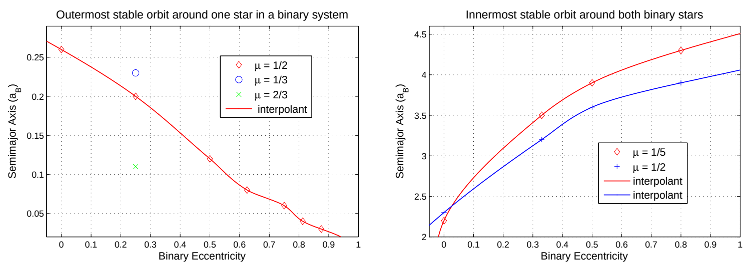

Figure 1. Orbital stability regions around one or both members of binary star systems. The left panel shows the *outermost* stable orbit around one star (in units of the binary semimajor axis) as a function of binary eccentricity for stellar mass ratios $\mu = 1/3$ (blue circle), 1/2 (red diamonds), and 2/3 (green x symbol). The right panel shows the *innermost* stable orbit around both stars for $\mu = 1/5$ (red diamonds) and 1/2 (blue + symbols).

stars and to gravitational interactions and completely inelastic collisions among the bodies.

We vary the stellar masses and orbital parameters (a_B and e_B), and perform multiple (3 – 30) simulations of each binary star system (with small changes in the initial conditions of one body in the disk) to account for the chaos in these N-body systems. Each system was evolved forward in time for 200 Myr – 1 Gyr. We also performed a large set of simulations around a Sun-like star (with and without giant planets) for a statistical comparison (Quintana & Lissauer 2006). Full details of all of our single and binary star accretion simulations are provided in Quintana et al. (2002); Quintana (2003, 2004); Lissauer et al. (2004); Quintana & Lissauer (2006); Quintana et al. (2007); Quintana & Lissauer (2007).

3. Planet Formation in the α Centauri AB Binary Star System

We first examined planetary accretion around each star in the α Centauri AB system (Quintana et al. 2002), which is comprised of a central binary consisting of the G2 star α Cen A (1.1 $M_\odot$) and the K1 star α Cen B (0.91 $M_\odot$). The stars have an orbital semimajor axis of 23.4 AU and an eccentricity of 0.52. The M5 star α Cen C (Proxima Centauri) is thought to orbit this pair (Wertheimer & Laughlin 2006), but at a very large distance ($\sim$12,000 AU), and is neglected in our calculations. Observations of α Centauri AB at the Anglo-Australian telescope imply that no planet orbiting either star induces periodic velocity variations as large as 2 m/s (G. Marcy, personal communication, 2006). This upper bound, combined with dynamical stability calculations (Wiegert & Holman 1997), implies that any planet in an S-type orbit around either component of the α Cen AB binary must have a mass less than that of Saturn or orbit in a plane that is substantially inclined to the line of sight to the system.

Simulations began with the initial inclination of the midplane of the disk, i, between 0 – 60°, and also 180° (retrograde), relative to the plane containing α Cen A and B. From 3 – 5 terrestrial planets formed around α Cen A, and

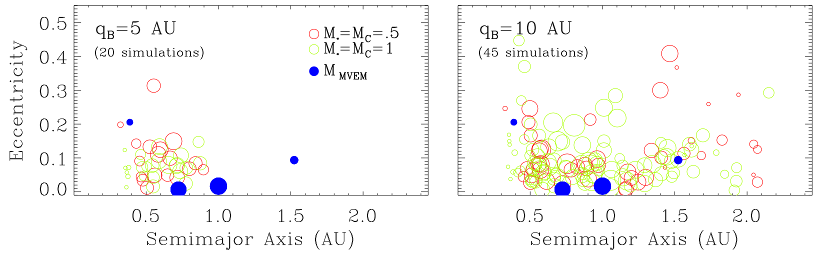

Figure 2. The distribution of the final planetary systems that formed around individual stars in binary star systems with periastron $q_B = 5$ AU (left panel) and 10 AU (right panel). The semimajor axis and eccentricity of each planet is shown, and the radius of each symbol is proportional to the radius of the planet that it represents. The terrestrial planets in our Solar System are represented by blue solid circles ('MVEM'). The formation of Earth-like planets near 1 AU was inhibited in all of our simulations with $q_B = 5$ AU.

from 2 – 4 planets formed around α Cen B, when the disk was initially inclined by 30° or less relative to the stellar orbit. In contrast, terrestrial planet growth around a star lacking both stellar and giant planet companions is an order of magnitude slower, and extended to larger semimajor axis, for the same initial disk (Quintana et al. 2002). In systems with $i = 45°$, from 2 – 5 planets formed, despite the fact that more than half of the disk mass was perturbed into the central star or ejected into interstellar space. When the disk was inclined by 60°, the stability of the planetary embryos decreased dramatically, and most of the bodies in the disk (98% of the initial mass, on average) were lost.

4. Circumstellar Planet Formation in 'Wide' Binary Star Systems

We performed a large survey of terrestrial planet formation in S-type orbits around one component of a binary star system (Quintana et al. 2007). We examined binary star systems with stellar mass ratios $\mu \equiv M_C/(M_\star + M_C) =$ 1/3, 1/2, or 2/3, where $M_\star$ is the mass of the star with a surrounding disk and M_C is the mass of the companion (each mass was set to either 0.5 or 1 $M_\odot$). The orbits (a_B and e_B) were chosen such that the binary periastron was one of three values, $q_B \equiv a_B(1 - e_B) = 5$, 7.5, or 10 AU. The binary stars were separated by $a_B = 10$, $13\frac{1}{3}$, 20, or 40, and the eccentricities were varied between $0 \leq e_B \leq 0.875$. The largest semimajor axis for which particles can be stable in any of the systems that we explore is 2.6 AU; we therefore did not include giant planets analogous to those in the Solar System (which orbit beyond 5 AU).

Figure 2 shows the final planetary systems that formed in all of the simulations in which the binary stars have $q_B = 5$ AU (left panel) or 10 AU (right panel). The periastron distance q_B clearly has a strong influence on where terrestrial planets can form in S-type orbits. The stellar companion truncates the disk when $q_B < 10$ AU. The median mass of the final planets, however, does not depend greatly on q_B, suggesting that planet formation remains quite efficient in the regions of stability. From 1 – 6 planets formed in all systems with $q_B =$

10 AU, from 1 – 5 planets remained in systems with $q_B = 7.5$ AU, and from 1 – 3 planets formed in all systems with $q_B = 5$ AU.

5. Circumbinary Planet Formation Around 'Close' Binary Stars

We examined planetary growth in P-type orbits by placing the same disk of planetesimals/embryos around an inner binary star system. The combined mass of the binary stars was equal to 1 $M_\odot$ in each case, with the stellar mass ratio μ equal to either 0.2 or 0.5. Binary star separations in the range $a_B = 0.05$ AU – 0.4 AU were examined, and e_B was either 0, 1/3, 0.5, or 0.8, such that the stellar apastron (the maximum stellar separation) $Q_B \equiv a_B(1+e_B)$ was between 0.05 AU $\leq Q_B \leq$ 0.4 AU. Giant planets analogous to Jupiter and Saturn at the present epoch were included.

Close binary stars with maximum separations $Q_B \lesssim 0.2$ AU and small e_B had little effect on the accreting bodies, and terrestrial planets formed over essentially the entire range of the initial disk mass distribution. Terrestrial planet systems that formed around binary stars with nonzero eccentricity were sparcer and more diverse. In our Solar System, perturbations from the giant planets restrict planet formation to within ∼2 AU. The binary stars, however, caused orbits to precess, thereby moving secular resonances out of the inner asteroid belt. In many simulations, terrestrial planets formed from our initially compact disk onto stable orbits as far as 3 AU from the center of mass of the binary stars. The effects of the stellar perturbations on the inner edge of the planetesimal disk became evident in systems with $Q_B \gtrsim 0.3$ AU, in which the formation of Earth-like planets near 1 AU was inhibited.

6. Summary and Implications for Habitable Extreme Solar Systems

Our numerical simulations show that terrestrial planet formation can indeed take place in a wide variety of binary star systems. To leading order, the binary apastron Q_B (the maximum stellar separation) is the most influential parameter for accretion in P-type orbits within circumbinary disks, and terrestrial planets similar to those in the Solar System formed around binary stars in simulations in which $Q_B \lesssim 0.2$ AU. Similarly, the periastron value q_B (the closest approach of the stars) is the most important parameter for planet formation on S-type orbits (more predictive than semimajor axis a_B or eccentricity e_B alone). In most simulations with $q_B = 10$ AU, terrestrial planets formed out to the edge of the initial planetesimal disk at 2 AU. When the periastron was as small as 5 AU, planets no longer formed with $a = 1$ AU orbits and $m_p < 1M_\oplus$, i.e., the formation of Earth-like planets was compromised.

Our simulations show that terrestrial planets can readily form around either star in α Cen AB. If terrestrial planets have indeed formed in α Cen AB, would such planets be habitable? Current models for the delivery of volatile materials to Earth (Morbidelli et al. 2000) suggest that the terrestrial planets received most of their volatiles from farther out in the solar system, principally from the asteroid belt. In the α Cen AB system (as well as the other wide binary systems described herein), orbits within most of the region analogous to that in which Earth's volatiles are believed to have formed into planetesimals are unstable on rapid dynamical timescales. Thus, material would not be expected to exist in these zones (at least after the gas-dominated disk was dispersed), and planets in α Cen AB would probably be dry, devoid of the C/H2O-based life that thrives on Earth. However, a recent analysis by Wertheimer & Laughlin (2006) shows that it is likely that α Cen C is bound to the α Cen AB system. Their results suggest that if a circumbinary disk exists around α Centauri AB, it is plausible that α Cen C could perturb volatiles from the circumbinary disk into the terrestrial planet regions of α Cen A and/or B, thereby providing a mechanism for planetary habitability.

Our planet formation simulations, along with orbital stability calculations (Wiegert & Holman 1997; David et al. 2003; Fatuzzo et al. 2006), suggest that $\sim$50% of the known binary systems are wide enough so that Earth-like planets (out to the distance of Mars's orbit) can remain stable over the entire 4.6 Gyr age of our Solar System. Furthermore, $\sim$10% of main sequence binaries are close enough to allow the formation and long-term stability of terrestrial planets in P-type circumbinary orbits ((David et al. 2003; Quintana & Lissauer 2006)). The results from all of our simulations can be scaled for different star and disk parameters with the formulae presented in Appendix C of Quintana & Lissauer (2006). Given that the galaxy contains more than 100 billion star systems, from contact binaries to separations of nearly a parsec, a large number of systems remain habitable based on the dynamic considerations of this research.

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