TERRESTRIAL PLANET FORMATION IN BINARY STAR SYSTEMS

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RESUMEN

El resumen será traducido al español por los editores. Most stars reside in binary/multiple star systems; however, virtually all previous models of planetary growth have assumed an isolated single star. Numerical simulations of the collapse of molecular cloud cores to form binary stars suggest that disks will form within binary star systems. Observations indirectly suggest the presence of disk material around one or both components within young binary star systems. If planets form at the right places within such disks, they can remain in stable orbits for very long times. We are simulating the late stages of growth of terrestrial planets within binary star systems, using two new symplectic integrators that we have developed for this purpose. We show that the late stages of terrestrial planet formation can indeed take place in a wide variety of binary systems, and we have begun to delineate the range of parameter space for which this statement is true. This paper presents results of our initial simulations of planetary growth around each star in the α Centauri AB system and in other 'wide' binary systems, as well as around both stars in close binary systems.

ABSTRACT

Most stars reside in binary/multiple star systems; however, virtually all previous models of planetary growth have assumed an isolated single star. Numerical simulations of the collapse of molecular cloud cores to form binary stars suggest that disks will form within binary star systems. Observations indirectly suggest the presence of disk material around one or both components within young binary star systems. If planets form at the right places within such disks, they can remain in stable orbits for very long times. We are simulating the late stages of growth of terrestrial planets within binary star systems, using two new symplectic integrators that we have developed for this purpose. We show that the late stages of terrestrial planet formation can indeed take place in a wide variety of binary systems, and we have begun to delineate the range of parameter space for which this statement is true. This paper presents results of our initial simulations of planetary growth around each star in the α Centauri AB system and in other 'wide' binary systems, as well as around both stars in close binary systems.

Key Words: **BINARY STARS — CIRCUMSTELLAR DISKS — CIRCUMBINARY DISKS — EXTRASOLAR PLANETS — PLANET FORMATION**

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 (Abt 1979, Duquennoy & Mayor 1991, Mathieu et al. 2000). Both circumstellar disks and circumbinary disks have been observed in young binary star systems, and thus a substantial fraction of planets (which form by an accretion process from dust and gas in a disk) may form in binary star systems. Furthermore, 19 extrasolar giant planets have been confirmed to travel on so-called S-type orbits that encircle one component of a binary (Eggenberger et al. 2004). Most of these extrasolar planets orbit stars whose stellar companion is quite far away, but 3 are in systems with stellar semimajor axes, a_B, of only ~ 20 AU. At least statistically, binarity seems to have an effect on planetary masses and orbits (Mazeh 2004, Eggenberger et al. 2004). Planets have yet to be detected in so-called P-type orbits that encircle both components of a binary star system, but close binaries are not included in precise Doppler radial velocity search programs because of their complex and varying spectra.

We are numerically simulating the final stages of terrestrial planet formation within binary star systems. Our goals are to determine whether/where terrestrial planet formation is possible from a disk of planetesimals/protoplanets on both S-type and P-type orbits for a variety of binary stars, and to characterize the resulting terrestrial planetary systems.

Our simulations assume that large bodies have already accreted from a circumstellar disk of gas and

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dust, and each run begins with a 'bimodal' mass distribution of 14 large embryos embedded in a disk of 140 smaller planetesimals. All solid bodies are assumed to have density $\rho = 3$ g cm^{-3}. These initial conditions were chosen because when they are used in simulations about a single star, they lead to systems that are similar to our Solar System. All collisions are assumed to be completely inelastic (perfect accretion), and the evolution of the accreting bodies are followed for 200 Myr – 1 Gyr. Because these N-body systems are chaotic in nature, we performed multiple integrations of each system with a slight change in the initial conditions of one body in the disk. This tactic allows us to sample the range of possible outcomes for effectively equivalent initial conditions. In these chaotic systems, the result is the distribution of outcomes, not a particular outcome.

The initial conditions and physical assumptions of our simulations are very similar to those of simulations of the final stages of terrestrial planet growth around single stars (Chambers 2001). Thus, we believe that comparison between our results and those of the single-star accretion simulations will delineate the effects of the binary star system on the accretion process despite our approximations, e.g., the lack of very small bodies and the assumption of perfectly inelastic collisions.

In this article, we present a summary of the results of our simulations of planetary growth on S-type orbits around each star in the α Centauri system (§2) and in other wide binary star systems (§3). In §4, we present results of our accretion simulations on P-type orbits around both stars in close binary systems. Details of the algorithms that we developed and the corresponding performance tests are presented in Chambers et al. (2002). Quintana (2004) provides the most complete discussion of our entire project.

2. PLANET FORMATION IN α CENTAURI

We have examined the late stages of terrestrial planet formation around each star in the α Centauri AB system, the closest binary system to the Sun. This binary is comprised of the G2 star α Cen A (1.1 $M_\odot$) and the K1 star α Cen B (0.91 $M_\odot$), which orbit one another with semimajor axis $a_B = 23.4$ and eccentricity $e_B = 0.52$.

From 3 – 5 terrestrial planets were formed around α Cen A in simulations for which the midplane of the disk was initially inclined by 30° or less relative to the binary orbital plane (Figures 1 and 2). When the embryos in the disk were moving retrograde relative to the binary plane, 4 or 5 terrestrial planets formed. From 2 – 5 planets formed in a disk centered around α Cen B, with α Cen A perturbing the system in the same plane. The distribution of resulting terrestrial planetary systems in the aforementioned cases is quite similar to that produced by calculations of terrestrial planet growth in the Sun-Jupiter or Sun-Jupiter-Saturn systems.

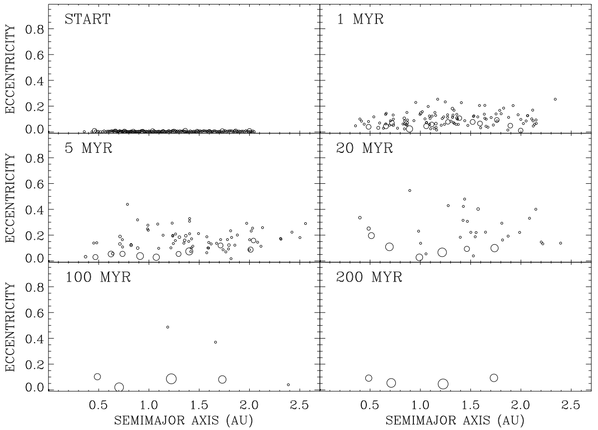

Fig. 1. The temporal evolution of a circumstellar disk centered around α Cen A, whose midplane was initially coplanar with the stellar orbit, is shown (simulation Ai0_4 in Quintana et al. 2002). The embryos' and planetesimals' eccentricities are displayed as a function of their semimajor axes, and the radius of each symbol is proportional to the radius of each body that it represents. After 200 Myr, four terrestrial planets were formed within 2 AU, accreting ∼ 88% of the initial disk mass. Similar evolution plots are presented for two simulations with nearly identical initial conditions but yielding 3 and 5 planets are shown in Figures 1 and 2 of Quintana et al. (2002). The differences between the simulations are produced by deterministic chaos, which implies that results of planetary accretion are extremely sensitive to changes in initial conditions. Thus, results are only valid in a statistical sense, and several simulations with very similar initial conditions must be run in order to adequately sample the distribution of possible outcomes.

In contrast, terrestrial planet growth around a star lacking both stellar and giant planet companions is slower and extends to larger semimajor axis for the same initial disk of planetary embryos (Quintana et al. 2002). Complementary simulations of terrestrial planet growth around α Centauri A by Barbieri et al. (2002), who varied the initial distribution of planetesimals substantially, yielded results that are consistent with those of our group.

In systems with the accreting disk initially inclined at 45° to the binary plane, from 2 – 5 planets formed despite the fact that more than half of the disk mass was scattered into the central star. When the disk was inclined at 60°, the stability of the planetary embryos decreased dramatically, and almost all

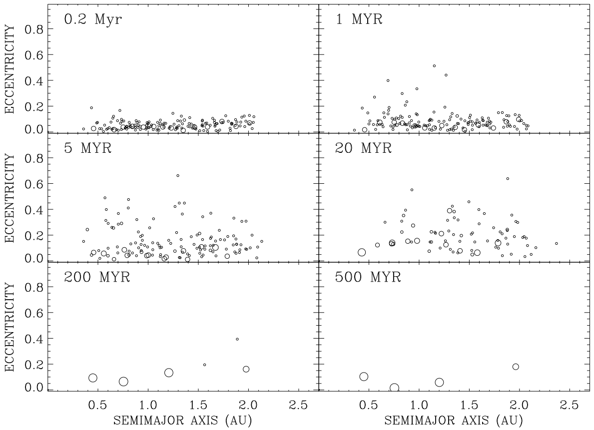

Fig. 2. The temporal evolution of a circumstellar disk centered around α Cen A, whose midplane was initially inclined 30° to the binary plane, is shown (simulation Ai30_1 in Quintana et al. 2002). The initial a–e distribution of the disk (not displayed here) is identical to that shown in the first panel of Figure 1. Note the similarity of the final system with Figure 1, despite a higher initial disk inclination.

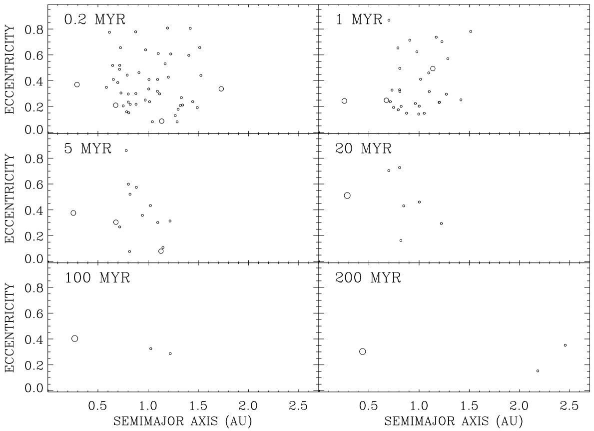

Fig. 3. The temporal evolution of our standard planetesimal disk centered around α Cen A, with its midplane initially inclined at $i = 60°$ to the stellar orbit, is shown here (simulation Ai60_2 in Quintana et al. (2002)). The binary companion's high initial inclination causes large variations in the eccentricity of each planetesimal and embryo, and most of the mass is perturbed into the central star within the first few million years. An evolution plot for a simulation with nearly identical initial conditions that yields a smaller single planet is shown in Figure 6 of Quintana et al. (2002).

of the planetary embryos and planetesimals were lost from these systems (e.g., Figure 3).

3. WIDE BINARY STAR SYSTEMS

We have begun investigating terrestrial planet accretion around one component within various binaries with stellar parameters differing from those of α Centauri. We show in Figures 4 and 5 the results of two of the ten realizations of planet formation within

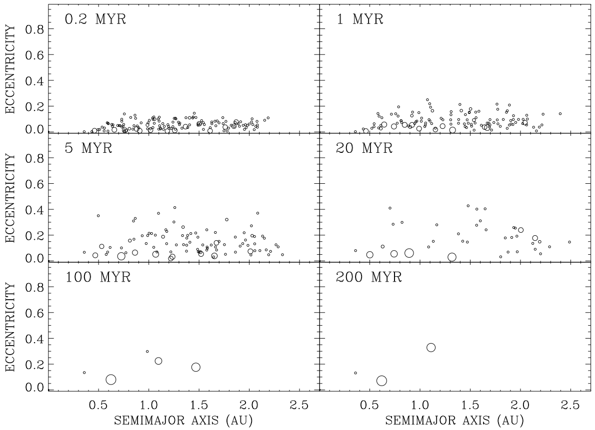

Fig. 4. The temporal evolution of our standard planetesimal disk centered around and coplanar to a 1 $M_{\odot}$ star, with another 1 $M_{\odot}$ star on an initially circular orbit perturbing the system at 10 AU.

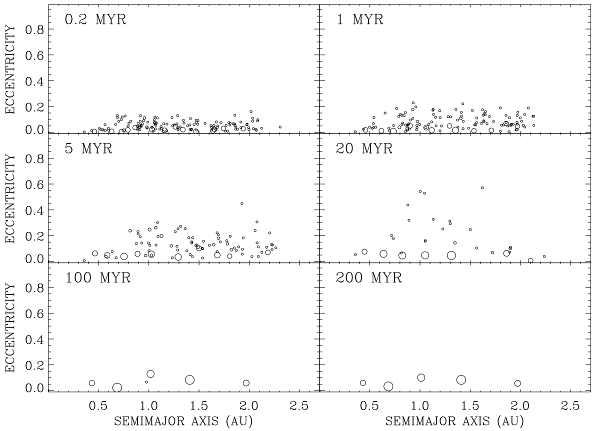

Fig. 5. Results of a simulation identical to that shown in Figure 4 aside from a 1 meter shift along its orbit in the initial position of one small body in the disk. Despite the smallness of this change, the final systems of terrestrial planets are very different.

binary systems composed of two $M_{\odot}$ stars with a_B = 10 AU and $e_B = 0.25$. Note the profound effects of chaos, which produces very different systems with only a trivial change in initial conditions.

A related question is that of the stability of planetary systems after they form. Numerical simulations of the long-term stability of Earth-like planets in orbit about a 1 $M_{\odot}$ star have shown that the stability is sensitive to the periastron $q_B = a_B(1 - e_B)$ of the stellar companion (e.g., David et al. 2003). These simulations suggest that Earth-like planets can remain on stable orbits for timescales on the order of the current age of the Solar System provided that $q_B \gtrsim 7$ AU. According to the observations of the distributions of binary orbital parameters by Duquennoy & Mayor (1991), about 50% of binary systems meet this constraint.

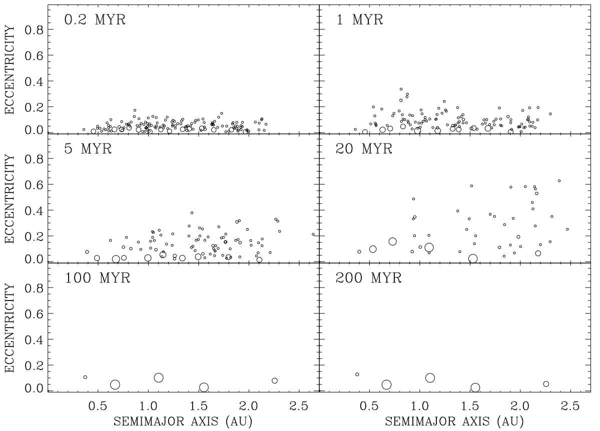

Fig. 6. The temporal evolution of our standard planetesimal disk shown in the first panel of Figure 1, but placed around two 0.5 $M_\odot$ stars with $a_B = 0.1$ AU, $e_B = i_B = 0$ (run CB_.1_0_0_.5_c in Quintana & Lissauer 2004), is shown.

4. CLOSE BINARY STAR SYSTEMS

We have performed simulations of the late stages of terrestrial planet formation within a circumbinary disk surrounding various short-period binary systems. In each case, the sum of the masses of the two stars is 1 $M_\odot$, and the initial disk of planetary embryos is the same as that used for simulating accretion within our Solar System and in the α Centauri AB system. When the stars travel on a circular orbit with a semimajor axis of up to 0.1 AU about their mutual center of mass, the planetary embryos grow into a system of terrestrial planets that is statistically indistinguishable from those formed about single stars (Figure 6), but a larger semimajor axis and/or a substantially eccentric binary orbit perturbs the planetesimals more strongly, typically leading to a system with fewer terrestrial planets (Figure 7).

5. STATUS

Our N-body simulations have shown the formation of terrestrial planets to be feasible around one or both components of a binary star system. Our numerical experiments for the α Centauri system have been completed and published (§2; Quintana et al. 2002); see Quintana (2003) for additional details concerning planet formation about α Centauri B. Our simulations of planet growth around both components of very close binary stars are almost complete and will be submitted for publication soon (§4; Quintana & Lissauer 2004). In the aforementioned article, we also discuss the scaling of results of planetary accretion simulation to systems with different stellar masses, planetesimal densities, etc. We are continuing our investigations of terrestrial planet accretion around one component of a binary, by examining a wider range of stellar masses and orbits (§3), to gain more insight into which parameters are most likely to affect the planet formation process.

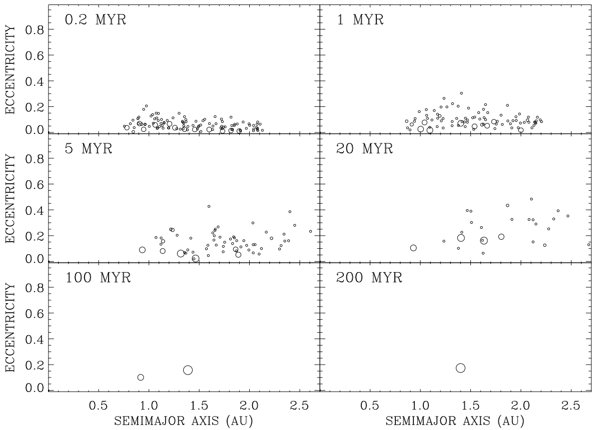

Fig. 7. Our standard planetesimal disk placed around two 0.5 $M_\odot$ stars with $a_B = 0.2$ AU and $e_B = 0.5$ (run CB_.2_.5_0_.5_a in Quintana & Lissauer 2004) results in the formation of only one planet at 1.4 AU.

6. ACKNOWLEDGEMENTS

This research is supported by a grant from NASA Ames Research Center's Director's Discretionary Fund, and in part by the University of Michigan through the Michigan Center for Theoretical Physics.

REFERENCES

Abt, H. A. 1979, AJ, 84, 1591

Barbieri, M., Marzari, F., Scholl, H. 2002, A&A, 396, 219

Chambers, J. E. 2001, Icarus, 152, 205

Chambers, J. E., Quintana, E. V., Duncan, M. J., & Lissauer, J. J. 2002, AJ, 123, 2884

David, E., Quintana, E. V., Fatuzzo, M., & Adams, F. C. 2003, PASP, 115, 825

Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485

Eggenberger, A., Udry, S., & Mayor, M. 2004, A&A, In Press

Mathieu, R. D., Ghez, A. M., Jensen, E. L. N., & Simon M. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. of Arizona Press), 703

Mazeh, T. 2004, in PASP Conference Series: Extrasolar Planets, Today & Tomorrow, Submitted

Quintana, E. V., Lissauer, J. J., Chambers, J. E., & Duncan, M. J. 2002, AJ, 576, 982

Quintana, E. V. 2003, in PASP Conference Series: Scientific Frontiers in Research on Extrasolar Planets, ed. D. Deming & S. Seager, 294, 319

Quintana, E. V. 2004, Ph.D. Thesis. Planet Formation in Binary Star Systems, University of Michigan, Ann Arbor.

Quintana, E. V., & Lissauer, J. J. 2004, In Preparation

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