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Terrestrial Planet Formation Around α Centauri B

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Abstract. The late stages of terrestrial planet formation ¡around each star in the α Centauri AB binary system are modeled using a recently developed symplectic algorithm designed to follow N-body systems with two dominant masses. Each integration begins with a circumstellar disk consisting of fourteen large embryos embedded in a disk of smaller planetesimals orbiting one star, and we follow the evolution of the accreting bodies for 200 Myr – 1 Gyr.

This paper describes simulations in which the circumstellar disk lies in the binary orbital plane and is centered around α Centauri B, and they are compared with recent simulations of terrestrial planet formation in the solar system. Simulations of terrestrial planet growth around α Cen A are discussed elsewhere (Quintana et al. 2002). In both cases, the binary companion has a similar effect on terrestrial planet formation around the central star as Jupiter and Saturn have around the sun; i.e., the companion determines an outer boundary for the terrestrial region but doesn't prevent the formation of terrestrial planets.

1. Introduction

Many of the $\sim$ 100 known extrasolar planets orbit stars which also possess a stellar companion, e.g., 16 Cygni B, τ Bootis, and 55 ρ Cancri (Cochran et al. 1997; Butler et al. 1997). The radial velocity technique used to discover these planetary companions is currently capable of detecting only Jupiter-mass planets, so the existence of Earth-sized planets in binary star systems still remains observationally unconstrained. Since more than half of all stars have at least one stellar companion (Abt 1977), it is worthwhile to examine terrestrial planet growth around one or both stars in a binary system.

The α Centauri system, the closest multiple-star system to the sun, 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 are separated by 23.4 AU and have a binary eccentricity of 0.52. The M5 star α Cen C (Proxima Centauri) is thought to orbit this pair at $\sim$ 12,000 AU, but is neglected in our simulations due to its negligible effect at this distance.

Previous test particle simulations of the α Cen binary system show that planets can be stable on orbits within $\sim$ 3 AU of either star (Wiegert & Holman 1997) for several million years. Further calculations by Marzari & Scholl (2000) show that planetesimals may accrete from a circumstellar disk of gas and dust within $\sim$ 2 AU of α Cen A. For our numerical simulations, we assume that planetesimals and larger planetary embryos have already formed from a dust disk centered around either α Cen A or α Cen B, and we follow the growth of planetary embryos subject to gravitational forces from the central star and the binary companion, and to inelastic collisions and gravitational forces between one another. We also examine the effects of chaos in these N-body systems by performing each integration a second time with a very slight change in the initial conditions of one body (one planetesimal near 1 AU is shifted by 1 meter along its orbit prior to the integration).

2. Numerical Model and Initial Conditions

To simulate the late stages of planetary accretion in binary star systems, we have incorporated an extra stellar perturbation into the *Mercury5* symplectic hybrid integrator (Chambers 1999; Chambers et al. 2002), which can also handle close approaches between bodies. Such algorithms, which are based on the N-body mapping technique of Wisdom & Holman (1991), are an order of magnitude faster than conventional integrators and do not produce a build-up of the energy error of a system.

The distribution of planetary embryos and planetesimals in a binary star system is at present poorly constrained. Thus, the mass distribution of the circumstellar disk is adopted from simulations of terrestrial planet growth in our own solar system (including Jupiter and Saturn, but no binary companion), which produced planetary configurations fairly similar to that actually observed (Chambers 2001). In this model, 14 'embryos' contain half of the disk mass while 140 'planetesimals' contain the other half. The radii of these bodies are calculated assuming a material density of 3 g cm^{-3}. The initial mass of each embryo is 0.0933 $M_\oplus$, and they are placed between 0.46 AU and 2.00 AU of the primary star. The planetesimals begin with a mass of 0.00933 $M_\oplus$ and range from 0.36 AU to 2.05 AU. The evolution of each system was followed for 200 Myr – 1 Gyr with a 7 day timestep.

3. Results and Discussion

Quintana et al. (2002) ran dozens of simulations of planet formation around α Cen A with various initial inclinations of the planetesimal disk relative to the binary orbital plane, several runs with the disk centered around α Cen B and coplanar with the binary orbit, and a few runs with the disk around a single star without giant planets for comparison purposes.

From 2 – 5 planets formed in all of our simulations with the disk around α Cen A, provided the inclination of the circumstellar disk began $\leq 30°$ to the binary orbit. The effect of the stellar companion became stronger as the disk inclination relative to the binary plane was increased (Quintana et al. 2002). In these cases, the stellar companion had a similar effect on planet accretion around the central star as simulations with Jupiter and Saturn had around the sun (the disk is truncated to within 2.5 AU, whereas it extends much further out in our single star simulations that do not include giant planets).

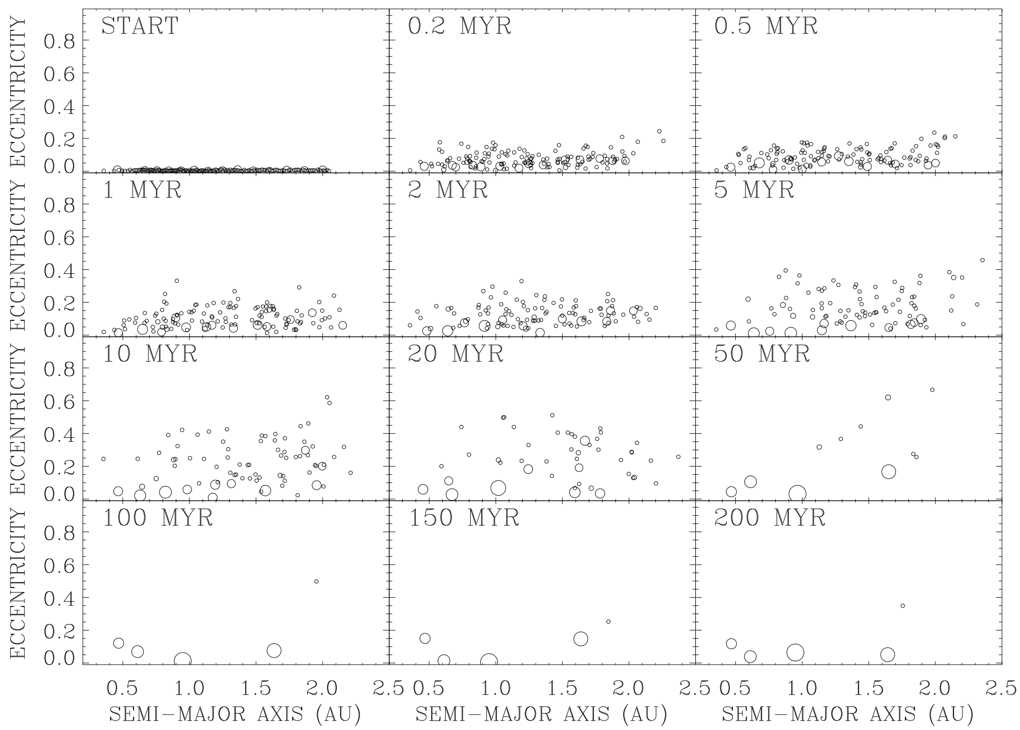

Figure 1. The evolution of a circumstellar disk centered around α Cen B is shown for a simulation in which the midplane of the disk coincides with the binary orbital plane. The eccentricities of all bodies in the disk are shown as a function of their semi-major axes, while the radius of each symbol is proportional to the radius of each body that it represents. In this 200 Myr simulation, four terrestrial planets have accreted within 1.6 AU of α Cen B, while one planetesimal remains on a highly eccentric orbit.

In simulations with the disk centered around α Cen B, the disk of accreting material is slightly more truncated compared with simulations with an analogous coplanar disk around α Cen A (due to α Cen A's larger mass), and the resulting planetary systems orbit closer to α Cen B. Figure 1 shows the results of our first simulation with the disk centered around α Cen B. The eccentricities and semi-major axes of all bodies in the disk are shown at various stages of the integration, and the radius of each symbol is proportional to the radius of the body that it represents. Within the first 10 million years, most of the more massive embryos remain below $e \sim 0.1$ while the planetesimals have a larger variation in their eccentricities (up to $e \sim 0.6$). Within 200 million years, four large planets have formed within 1.7 AU. An Earth-analogue at 0.985 $M_\oplus$ remains at 0.95 AU with $e = 0.2$. Figure 2 shows the results of a system with identical initial conditions as Figure 1, with the exception of an initial 1m shift of one planetesimal prior to the integration. Because these N-body systems are chaotic, this small change in initial starting conditions ultimately effect the final planetary states, and in this simulation three large planets form within 1.1 AU of α Cen B. In an additional

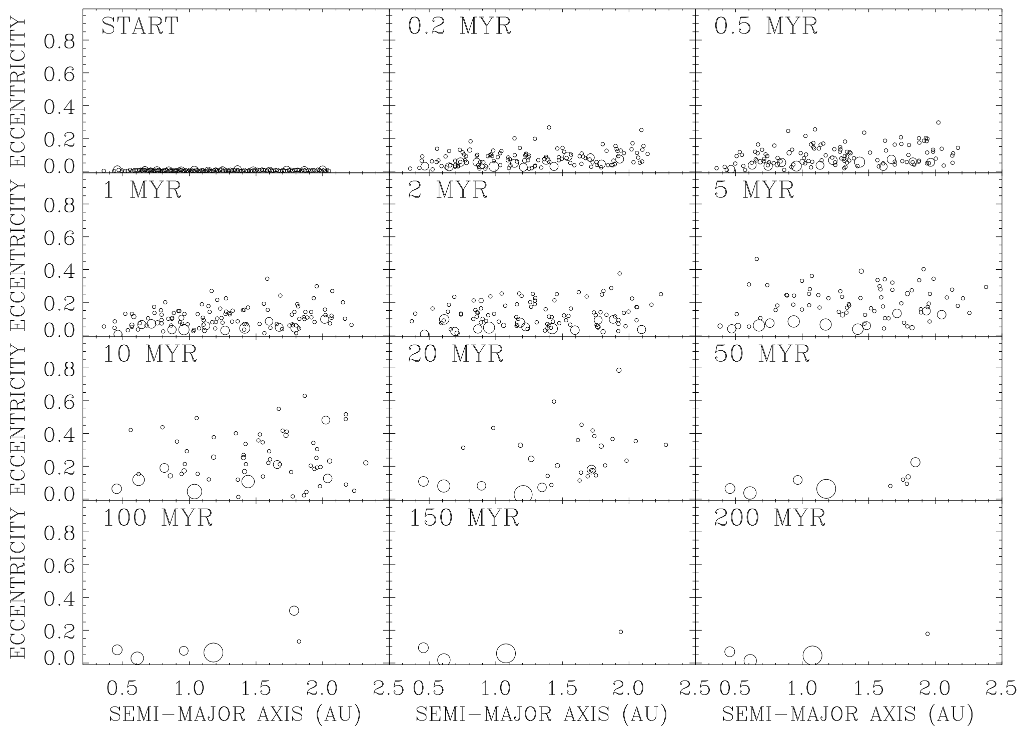

Figure 2. The evolution of a system with identical initial conditions as the system shown in Figure 1, with the exception of a 1m shift of one planetesimal in the disk prior to the integration, is shown here. This small change in initial conditions results in the formation of three terrestrial planets within 1.1 AU of α Cen B, with one planetesimal remaining at 1.9 AU.

pair of simulations with the disk around α Cen B, 2 – 3 terrestrial planets formed within 1.3 AU (in one case a 1.2 $M_\oplus$ planet remained at 0.97 AU). It is plausible that terrestrial planets with similar masses and orbits to those within our solar system may have formed around α Cen A or B, despite the proximity of these two stars.

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