# Formation and Detectability of Terrestrial Planets around $\alpha$ Centauri B

Guedes, J. M., Rivera, E. J., Davis, E., Laughlin, G.

*Department of Astronomy and Astrophysics, University of California, 1156 High Street, Santa Cruz, CA 95060*

Quintana, E. V.

*SETI Institute, 515 N. Whisman Road, Mountain View, CA 94043*

Fischer, D. A.

*Department of Physics and Astronomy, San Francisco State University, San Francisco, CA*

## ABSTRACT

We simulate the formation of planetary systems around $\alpha$ Centauri B. The N-body accretionary evolution of a $\Sigma \propto r^{-1}$ disk populated with 400-900 lunar-mass protoplanets is followed for 200 Myr. All simulations lead to the formation of multiple-planet systems with at least one planet in the 1-2 $M_\oplus$ mass range at 0.5-1.5 AU. We examine the detectability of our simulated planetary systems by generating synthetic radial velocity observations including noise based on the radial velocity residuals to the recently published three planet fit to the nearby K0V star HD 69830. Using these synthetic observations, we find that we can reliably detect a 1.8 $M_\oplus$ planet in the habitable zone of $\alpha$ Centauri B after only three years of high cadence observations. We also find that the planet is detectable even if the radial velocity precision is 3 $\mathrm{m\,s^{-1}}$, as long as the noise spectrum is white. Our results show that the greatest uncertainty in our ability to detect rocky planets in the $\alpha$ Centauri system is the unknown magnitude of ultra-low frequency stellar noise.

*Subject headings:* binaries: general — planetary systems: formation — planetary systems: protoplanetary disks — stars: individual (Alpha Centauri B)

## 1. Introduction

In the past decade, over 270 extrasolar planets have been discovered in a plethora of diverse environments. Earth-like planets in habitable-zone orbits, however, remain well below

the threshold of detection. A good representation of the Doppler velocity state-of-the-art is presented by the triple planet system orbiting HD 69830. This system has been shown to contain three Neptune-mass planets, including one on a 197-day orbit, all revealed after only 74 radial velocity observations with residual noise of 0.6 $\mathrm{m\,s^{-1}}$ (Lovis et al. 2006). The detection of the HD 69830 system suggests that focused efforts on selected stars may be able to probe down to the characterization of planets with radial velocity half-amplitudes considerably below 1 $\mathrm{m\,s^{-1}}$. Targeted planet search around nearby stars may prove to be an efficient and inexpensive path to detection. Simulations of transiting terrestrial planets around low-mass stars show that an array of 10 meter-size telescopes can unveil these planets within a year (Montgomery & Laughlin 2007) . In this paper, our goal is to argue that the $\alpha$ Centauri system provides a remarkable test-bed for pushing the Doppler detection envelope.

The $\alpha$ Centauri system, with $d$=1.33 pc, is the Sun's closest neighbor. It is a triple star system composed of the central $\alpha$ Cen AB binary and the M dwarf Proxima Cen, which orbits the AB pair with a semi-major axis of over 10,000 AU (Wertheimer & Laughlin 2006). The G2V star $\alpha$ Cen A and the K1V $\alpha$ Cen B have masses similar to the Sun with $M_A = 1.105 \pm 0.007 M_\odot$ and $M_B = 0.934 \pm 0.007 M_\odot$ while the M dwarf Proxima Cen is significantly smaller with $M_C = 0.107 \pm 0.021 M_\odot$ (Pourbaix et al. 2002). Though both A and B have super-solar metallicities $[Fe/H]_A = 0.22 \pm 0.02$ and $[Fe/H]_B = 0.26 \pm 0.04$ (Chmielewski et al. 1992), no planets with masses comparable to Neptune or larger have yet been found orbiting either star.

Astronomical observations of $\alpha$ Cen A and B have been conducted for over 150 years. Astrometric observations date back to the first half of the nineteenth century, and the radial velocities of both components have been tabulated since 1904. Pourbaix et al. (2002) simultaneously fit all the published astrometric measurements and radial velocities of both components to constrain the binary orbital parameters. (See their reference list for an historical listing of publications relating to observations of $\alpha$ Cen A and B.) A similar study had been done by Pourbaix et al. (1999). In the earlier study, after fitting for the binary orbit, they examined the plausibility of planetary companions and found that they could have detected a planetary companion with a mass above 10 $M_{\rm Jup}$. Endl et al. (2001) performed a similar, but more sensitive analysis, using the orbit of Pourbaix et al. (1999) and their own high precision ESO Coudé Echelle Spectrometer radial velocities. They found upper limits for planets on circular orbits at any orbital radius around each component of 2.5 $M_{\rm Jup}$ for $\alpha$ Cen A and 3.5 $M_{\rm Jup}$ for $\alpha$ Cen B. We performed a procedure in which we used the parameters from Pourbaix et al. (2002) and their radial velocities and those from Endl et al. (2001) for $\alpha$ Cen B. We used the systemic console (Rivera et al. 2008 in prep.), to fit only the mean anomaly and the velocity offsets between the three data sets. The remaining parameters were held fixed. If we simply assume that the RMS of the fit, 9 $\mathrm{m\,s^{-1}}$, corresponds to the

upper limit of the radial velocity half amplitude of a planet in a circular orbit at 1 AU or at 3 AU, then the corresponding upper limit on the mass of the planet is $\sim$0.3 $M_{\rm Jup}$ or $\sim$0.5 $M_{\rm Jup}$, respectively. This also follows from the formula for the radial velocity half amplitude $K$ of a planet of mass $m_{pl}$, period $P$, and eccentricity $e$ orbiting a star of mass $M_\star$ with orbital inclination relative to the plane of the sky $i$,

$$K = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{m_{pl}\sin i}{(M_\star + m_{pl})^{2/3}} \frac{1}{\sqrt{1-e^2}} \sim 29.8 \frac{m_{pl}\sin i}{\sqrt{M_\star a}} \mathrm{m\,s^{-1}}, \tag{1}$$

where for the last relation, Kepler's third law is applied, $m_{pl} \ll M_\star$, $e = 0$, and the units for $m_{pl}$, $M_\star$, and $a$ are in $M_\oplus$, $M_\odot$, and AU, respectively.

Several studies of $\alpha$ Cen A and B show that terrestrial planet formation is possible around both stars despite their strong binary interaction (Quintana et al. 2002, 2006, 2007). Results to date consistently indicate that planetary systems with one or more Earth-mass planets can form within 2.5 AU from the host stars and remain stable for gigayear scales. Numerical simulations and stability analyzes of planetesimal disks indicate that material is stable within 3 AU from A/B, as long as the inclination of the disk with respect to the binary is $\lesssim 60^\circ$ (Quintana et al. 2002; Wiegert & Holman 1997). In essence, with regard to the formation process, the companion star plays the perturbative role that the gas giants in our solar system are believed to have played during the formation phases of the Sun's terrestrial planets. The perturbations allow for the accretion of a large number of planetary embryos into a final configuration containing 3-4 bodies (Quintana et al. 2002). Circumprimary planet formation is known to occur in binary systems and despite observational selection biases, $\sim$ 20% of all planets discovered to date belong to multiple systems (Eggenberger & Udry 2007). Of the binaries that are known to harbor planets, three (HD 41004, $\gamma$ Cephei, and Gl86) have projected semi-major axes of $\simeq$ 20 AU, an orbital separation similar to that of the AB pair.

In this paper we assess the detectability of terrestrial planets around $\alpha$ Cen B. We begin by carrying out eight simulations of the late stage of planet formation using the initial conditions detailed in § 2. A brief description of the systems we formed is given in § 3. Each planetary system is then tested for detectability using a Monte Carlo method for generating synthetic radial velocity observations, as described in § 4. Based on our results, we are able to accurately evaluate the detectability of planetary systems around the star. Finally, in § 5 we summarize our work and discuss our results.

## 2. Initial Conditions

The initial conditions of the circumstellar disk in our simulations mimic conditions at the onset of the chaotic growth phase of terrestrial planet formation (Kokubo & Ida 1998; Kenyon & Bromley 2006) in which collisions of isolated embryos, protoplanets of approximately lunar mass, dominate the evolution of the disk. During this phase, gravitational interactions among planetary embryos serve to form the final planetary system around the star and clear out the remaining material in the disk. At the start of this phase, several hundred protoplanets orbit the star on nearly circular orbits.

We model the $\alpha$ Centauri B circumstellar disk with a $\Sigma = \Sigma_0(a/1AU)^{-1}$ surface density profile where $\Sigma_0 = 8.4 - 18.8$ g cm$^{-2}$ as calculated from the total mass $M = Nm$, where $N$ is the number of protoplanetary embryos in the disk and $m$ is the embryo's mass. These surface densities are based on disks modeled by Chambers (2001) and account for the enhanced metallicity of $\alpha$ Cen B with respect to the Sun. The disk extends from $1 < a < 3.5$ AU and it is coplanar with the binary orbit. For each run, we populate the disk with $N = 400$ to $N = 900$ embryos of lunar mass ($m = 0.0123 M_\oplus$) with semi-major axes chosen via a rejection method in $a$ to obtain a $\Sigma \propto r^{-1}$ density profile.

Initial orbital elements of each embryo are randomly generated with mean anomalies, arguments of pericenter, and longitudes of ascending node extending from 0° to 360°, eccentricities in the range $0 < e < 0.001$, and inclinations in the range $0° < i < 1°$ with respect to the plane of the binary.

Integrations are run using a specialized version of the symplectic hybrid integrator in the MERCURY integration package (Chambers 1999). This $N$-body code is designed to study planet growth in the presence of a binary companion (Chambers et al. 2002). Bodies grow via accretion through perfectly inelastic embryo-embryo collisions, and therefore close encounters are integrated directly rather than symplecticaly. Each simulation was evolved for 200 Myr, consuming a total of ∼600 cpu hours on several (dual) Intel Xeon machines with clock speeds of at least 2.2 GHz.

We focus on terrestrial planet formation around $\alpha$ Cen B, for which we perform a total of eight integrations named rN_n, where N is the initial number of protoplanets and n is an identifier. For instance, r700_2 corresponds to our second simulation of a disk initially containing 700 bodies. As shown in Quintana et al. (2002) and Quintana et al. (2007), planet formation around $\alpha$ Cen A is expected to be qualitatively similar.

## 3. Terrestrial Planet Formation

Our $N$-body simulations take place in the wide binary regime, with $\alpha$ Cen B as the central star and $\alpha$ Cen A orbiting with binary semi-major axis $a_{AB} = 23.4$ AU and eccentricity $e_{AB} = 0.52$ (Pourbaix et al. 2002). We adopt the stellar masses to be $M_A = 1.105 M_\odot$ and $M_B = 0.934 M_\odot$ (Pourbaix et al. 2002) and radii $R_A = 1.224 R_\odot$ and $R_B = 0.862 R_\odot$ (Kervella et al. 2003). Due to its low mass and large distance from the AB pair, Proxima Cen is neglected in our simulations.

Figure 1 shows the late evolutionary stage of a protoplanetary disk initially containing 600 moon-mass embryos (r600_1, see Figure 2 and Table 1). The radius of each circle is proportional to the radius of the object. Bodies in the outer parts of the disk ($a > 3$ AU) are immediately launched into highly eccentric orbits and either migrate inward to be accreted by inner bodies, collide with the central star, or are ejected from the system ($a_{ej} = 100$ AU). In this simulation, $\sim 65\%$ of the total initial mass is cleared within the first 70 Myr. By the end of simulation r600_1, four planets have formed. One planet has approximately the mass of Mercury and is located at $a = 0.2$ AU, two 0.6 $M_\oplus$ planets form at $a = 0.7$ and $a = 1.8$ AU, and a 1.8 $M_\oplus$ planet forms at $a = 1.09$ AU.

Table 1 shows the orbital elements of the final systems that emerge from the calculations. All of our simulations result in the formation of 1-4 planets with semi-major axes in the range $0.7 < a < 1.9$ AU, in agreement with Quintana et al. (2002). We find that 42 % of all planets formed with masses in the range 1-2 $M_\oplus$ reside in the star's habitable zone (Fig. 2), taken to be $0.5 < a_{hab} < 0.9$ (Kasting et al. 1993).

As a general trend, we find that disks with higher initial surface densities are able to retain more mass (see figure 3) but do not necessarily form more planets (see table 1). All of our disks form systems with one or two planets in the 1-2 $M_\oplus$ mass range.

## 4. Detectability

### 4.1. Why $\alpha$ Cen B is the Best Radial Velocity Candidate Star in the Sky

The radial velocity detection of Earth-mass planets near the habitable zones of solar type stars requires $\mathrm{cm\,s^{-1}}$ precision. $\alpha$ Cen B is overwhelmingly the best star in the sky for which one can contemplate mounting a high-cadence search.

Both $\alpha$ Cen A and B have relatively high metallicities, with $[Fe/H]_A = 0.22$ for A and $[Fe/H]_B = 0.26$ for B (Chmielewski et al. 1992) and therefore would have been presumably

endowed with circumprimary disks containing a relatively high fraction of solid material. Simulations such as the ones we have performed and others indicate that the final mass present in terrestrial planets is in direct proportion to the initial amount of material available.

$\alpha$ Cen B is exceptionally quiet, both in terms of acoustic p-wave mode oscillations and chromospheric activity. Observations of $\alpha$ Cen A with the UVES Echelle Spectrograph show that the star exhibits p-mode oscillations with amplitude varying from 1-3 $\mathrm{m\,s^{-1}}$ and a periodicity of ∼5 minutes (Butler et al. 2004). UVES observations of $\alpha$ Cen B show that peak amplitude noise for this star is much lower, reaching only 0.08 $\mathrm{m\,s^{-1}}$ (Kjeldsen et al. 2005). Furthermore, the average noise lies in the frequency range 7.5-15 mHz for $\alpha$ Cen A and 4.1 mHz for $\alpha$ Cen B. These frequencies are far higher than the $10^{-5}$ to $10^{-4}$ mHz frequency range associated with the periods of the putative terrestrial planets. A focused high cadence approach involving year-round, all-night observations would effectively average out the star's p-mode oscillations. The long and short term chromospheric variability of the $\alpha$ Cen system was studied by Robrade, Schmitt, & Favata (2005) using X-ray data taken with XMM-Newton over a period of two years. They find that $\alpha$ Cen A's X-ray luminosity declined by a factor of ten in this time period, an indication of a moderate coronal activity. In turn, $\alpha$ Cen B's X-ray brightness varied only within a factor of two, denoting rather low short-term chromospheric activity associated with weak stellar flares. To date, no long-term variability has been detected in either star.

$\alpha$ Cen B is remarkably similar in age, mass, and spectral type to HD 69830, the nearby K0 dwarf known to host three Neptune-mass planets (Lovis et al. 2006). Both $\alpha$ Cen B and HD 69830 are slightly less massive than the Sun with masses 0.91 $M_\odot$ and 0.86 $M_\odot$, respectively. Their estimated ages are 5.6-5.9 Gyr for $\alpha$ Cen B (Yildiz 2007) and 4-10 Gyr for HD 69830. Both stars are slightly cooler than the Sun: $\alpha$ Cen B is a K1V with $T_{eff} = 5,350$ K, while HD 69830 is a type K0V star with $T_{eff} = 5,385$ K. The stars have also similar visual absolute magnitudes, $M_V = 5.8$ for $\alpha$ Cen B and $M_V = 5.7$ for HD 69830 (Perryman et al. 1997); however, due to its proximity to us, the former star appears much brighter ($m_V = +1.34$), allowing for exposures that are ∼60 times shorter. One can thus use a far smaller-aperture telescope, or alternatively, entertain a far higher observational cadence. Indeed, $\alpha$ Cen B is so bright that the CCD readout will be the primary limiter to an observational strategy. Furthermore, immediate proximity to $\alpha$ Cen A provides the opportunity to create a parallel set of observations for both stars. Periodicities common to both stars would be indicative of erroneous signals being introduced by the observational pipeline itself. An advantage of $\alpha$ Cen B over HD 69830 is its increased metallicity ([Fe/H] = 0.26 vs. [Fe/H] = -0.05). Higher metallicity leads to deeper lines, which can improve the precision of Doppler velocities. Oscillatory p-mode noise for HD 69830 was estimated to lie between 0.2 and 0.8 $\mathrm{m\,s^{-1}}$ (Lovis et al. 2006), reaching the upper limit of the p-mode noise

expected for $\alpha$ Cen B.

Because $\alpha$ Cen B is sightly less massive than the Sun, terrestrial planets would induce a larger radial velocity half-amplitude (Earth induces a 9 $\mathrm{cm\,s^{-1}}$ reflex velocity on the Sun). Also, $\alpha$ Cen B is significantly less luminous than the Sun and thus its habitable zone is closer in (Kasting et al. 1993). Yet another advantage is the fact that planets should be close to circumplanar with the binary plane, which is inclined only 11° to the line of sight to Earth. This ensures that $\sin i \simeq 1$, and that the planets will contribute nearly their full mass to the observed radial velocity half-amplitude.

Finally, the system is perfectly positioned in the southern sky. $\alpha$ Centauri lies at $-60°$ declination, allowing for observations nearly 300 days out of the year at the latitude of the Las Campanas Observatory or the Cerro Tololo International Observatory in Chile.

All these criteria make $\alpha$ Cen B the ideal host and candidate for the detection of a planetary system that contains one or more terrestrial planets.

### 4.2. Synthetic Data

We took the orbital elements of the systems emerging from our simulations and generated model radial velocities. We developed a code which effectively simulates the observing conditions for any specific location on Earth. Given the latitude and longitude of an observatory and the RA and DEC of an object, the code determines when the object is observable. Two additional inputs concern the beginning and end of an observing night: the angle of the sun below the local horizon and the maximum airmass of the object, beyond which observing should not continue. Some fraction of nights are lost to emulate adverse weather conditions and other effects which could result in missed observations. For this paper we assumed a 25% probability for the loss of a night. We assumed access to a dedicated telescope at Las Campanas Observatory. At this location, $\alpha$ Centauri is observable for about 10 months out of the year. We assumed an observing cadence of one exposure every 200 seconds, corresponding to the read out time of the detector (this is a conservative estimate, since in practice we would expect a considerably higher duty cycle). Finally, we assumed various values of Gaussian white noise to add to the model radial velocities.

Figure 4 shows a simulated set of radial velocities for the system represented in run r600_1. In this case, we assumed Gaussian white noise with amplitude 3 $\mathrm{m\,s^{-1}}$. It is important to note that the model radial velocity for $\alpha$ Cen B due to the four terrestrial planets in this system has an amplitude of 23 $\mathrm{cm\,s^{-1}}$, or a factor of 13 below the noise. Over the five year span, 97,260 measurements can be obtained. For this example, we find that we can

confidently detect 2 or 3 planets in this time span. Most of the currently known extrasolar planets were announced after the false alarm probability (FAP) for seeing a peak in the periodogram of the radial velocity data fell below ∼1%. Many were announced after the FAP fell below this level and additional (and sometimes extensive) statistical tests of significance were performed. Using the 1% FAP as an initial indicator of the significance of a detection for the example discussed here, we can confidently detect at least one of the planets after about the first three years of observations.

In the absence of significant coloration to noise, the example shown in figures 4 and 5 is a pessimistic case. In keeping with the fact that the star is a virtual twin of HD 69830 (Lovis et al. 2006), $\alpha$ Cen B is expected to show very little radial velocity noise or jitter. The detection of three Neptune mass planets around HD 69830 was facilitated by the small instrumental uncertainties for its radial velocity observations, with a median value of ≈0.7 $\mathrm{m\,s^{-1}}$, along with the assumption of a very small long-term stellar jitter. For the example shown in Figures 4 and 5, and assuming an optimistic level of Gaussian noise with amplitude ≈0.7 $\mathrm{m\,s^{-1}}$, the largest peaks in the periodograms in Figure 5 would have power of order 10 times greater. Additionally, those peaks would have significantly smaller FAP's, and these FAP's would clearly reach the 1% level in less time than in the case with a larger amount of noise. Thus, at least the first planet would have been clearly detected within the first two years, and at least 3 of the planets would have been detected after five years.

Assuming that 3 $\mathrm{m\,s^{-1}}$ Gaussian white noise is an upper limit to the level of radial velocity noise expected for $\alpha$ Cen B, and that small terrestrial planets ($M_P \lesssim 2\,M_\oplus$) orbit this star within 3 AU, high cadence, relatively moderate term radial velocity observations should clearly detect at least one of these planets. Our simulations and those of Quintana et al. (2007) show that for disks with small inclinations relative to the binary orbit, large terrestrial planets tend to form in or near the habitable zone of $\alpha$ Cen B. Thus, it is possible we may detect a habitable terrestrial planet around at least one of our nearest stellar neighbors.

This is true for all the models explored and for an assumed Gaussian white noise source with amplitude up to 3 $\mathrm{m\,s^{-1}}$, which is likely much larger than the expected jitter for $\alpha$ Cen B.

## 5. Discussion

The space density of binary systems containing roughly solar-mass components is roughly $n = 0.02$ $\mathrm{pc^{-3}}$. We are thus remarkably lucky that the $\alpha$ Cen system is currently only 1.33 pc away. The possibility that detectable terrestrial planets are orbiting $\alpha$ Cen B does much

to fire the imagination, and indeed, a positive identification of such a planet would be a truly landmark discovery. $\alpha$ Cen's proximity allows one to envision space-based follow-up efforts (astrometric, coronographic, interferometric) to characterize the planets that would be far more difficult to carry out for planets orbiting less luminous and more distant stars.

Alternately, or to phrase the situation another way, our current understanding of the process of terrestrial planet formation strongly suggests that *both* components of the $\alpha$ Cen system should have terrestrial planets. A lack of planets orbiting these stars would thus provide a critical hint that there is a significant qualitative gap in our understanding of planet formation.

The situation is thus as follows. A successful detection of terrestrial planets orbiting $\alpha$ Cen B can be made within a few years and with the modest investment of resources required to mount a dedicated radial-velocity campaign with a 1-meter class telescope and high-resolution spectrograph. The plan requires three things to go right. First, the terrestrial planets need to have formed, and they need to have maintained dynamical stability over the past 5 Gyr. Second, the radial velocity technique needs to be pushed (via unprecedentedly high cadence) to a degree where planets inducing radial velocity half-amplitudes of order $\mathrm{cm\,s^{-1}}$ can be discerned. Third, the parent star must have a negligible degree of red noise on the ultra-low frequency range occupied by the terrestrial planets.

In this paper, we've made the case that conditions 1 and 2 are highly likely to have been met. In our view, the intrinsic noise spectrum of $\alpha$ Centauri B is likely all that stands between the present day and the imminent detection of extremely nearby, potentially habitable planets. Because whole-sun measurements of the solar noise are intrinsically difficult to obtain, our best opportunity to measure microvariability in radial velocities is to do the $\alpha$ Cen AB Doppler experiment. The intrinsic luminosity of the stars, their sky location, and their close pairing will allow for a definitive test of the limits of the radial velocity technique. If these limits can be pushed down to the $\mathrm{cm\,s^{-1}}$ level, then the prize, and the implications, may be very great indeed.

We thank the anonymous referee for providing useful comments that improved our paper. This research was conducted with financial support from NASA PGG grant NNG04GK19G and NSF grant AST 0049986 to G.L and a NSF Graduate Research Fellowship to J.M.G.

## REFERENCES

Butler, R. P., Bedding, T. R., Kjeldsen, H., McCarthy, C., O'Toole, S. J., Tinney, C. G., Marcy, G. W., & Wright, J. T. 2004, ApJ, 600, L75

Chambers, J. E. 2001, Icarus 152, 205, 224

Chambers, J. E. 1999, MNRAS, 304, 793

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

Chambers, J. E., & Wetherill, G. W. 1998, Icarus, 136, 304

Chmielewski, Y., Friel, E., Cayrel de Strobel, G.,& Bentolila, C. 1992, A&A, 263, 219

Eggenberger, A. & Udry, S. 2007, astro-ph/0705.3173

Endl, M., Kürster, M., Els, S., Hatzes, A. P., & Cochran, W. D. 2001, A&A, 374, 675

Kasting, J. F., Whitmire, D. P., & Reynolds, R. T. 1993, Icarus, 101, 108

Kenyon, S. J., & Bromley, B. C. 2006, AJ, 131, 1837

Kervella, P., Thévenin, F., Ségransan, D., Berthomieu, G., Lopez, B., Morel, P., & Provost, J. 2003, A&A, 404, 1087

Kjeldsen, H., et al. 2005, ApJ, 635, 1281

Kokubo, E., & Ida, S. 1998, Icarus, 131, 171

Lovis, C. et al., 2006, Nature, 441, 305

Montgomery, R. & Laughlin, G., Icarus (submitted)

Perryman, M. A. C., et al. 1997, A&A, 323, L49

Pourbaix, D., Neuforge-Verheecke, C., & Noels, A. 1999, A&A, 344, 172

Pourbaix, D., et al. 2002, A&A, 386, 280

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

Quintana, E. V., & Lissauer, J. J. 2006, Icarus, 185, 1

Quintana, E. V., Adams, F. C., Lissauer, J. J., & Chambers, J. E. 2007, ApJ, 660, 807

Robrade, J., Schmitt, J. H. M. M., & Favata, F. 2005, A&A, 442, 315

Wertheimer, J. G. & Laughlin G. 2006, AJ, 132, 1995

Wiegert, P. A., & Holman, M. J. 1997, AJ, 113, 1445

Yildiz, M. 2007, MNRAS, 374, 1264

Table 1: Simulation Results

| Run | $N$ | $\Sigma_0$ [ g cm$^{-2}$ ] | planet | $M$ [ $M_\oplus$ ] | Period [ yr ] | $a$ [ AU ] | $e$ | $I$ [°] |
|---|---|---|---|---|---|---|---|---|
| r900_1 | 900 | 18.8 | a | 2.054 | 0.760 | 0.806 | 0.052 | 1.585 |
| | | | b | 0.922 | 2.412 | 1.734 | 0.051 | 5.784 |
| | | | c | 0.036 | 0.361 | 0.491 | 0.094 | 18.108 |
| | | | d | 1.291 | 1.464 | 1.248 | 0.145 | 5.391 |
| r800_1 | 800 | 16.7 | a | 0.086 | 0.227 | 0.361 | 0.244 | 19.135 |
| | | | b | 1.316 | 0.495 | 0.606 | 0.105 | 1.639 |
| | | | c | 1.279 | 1.453 | 1.242 | 0.168 | 2.042 |
| r800_2 | 800 | 16.7 | a | 0.996 | 1.769 | 1.419 | 0.169 | 6.034 |
| | | | b | 0.098 | 0.441 | 0.663 | 0.325 | 8.259 |
| | | | c | 2.435 | 0.835 | 0.858 | 0.024 | 3.759 |
| r700_1 | 700 | 14.7 | a | 0.897 | 2.262 | 1.669 | 0.198 | 4.965 |
| | | | b | 2.165 | 0.812 | 0.843 | 0.142 | 4.516 |
| r700_2 | 700 | 14.7 | a | 1.820 | 0.767 | 0.811 | 0.016 | 1.846 |
| | | | b | 1.107 | 1.640 | 1.346 | 0.032 | 3.064 |
| r700_3 | 700 | 14.7 | a | 2.755 | 0.944 | 0.931 | 0.217 | 4.391 |
| r600_1 | 600 | 12.6 | a | 0.565 | 2.585 | 1.831 | 0.181 | 3.979 |
| | | | b | 0.578 | 0.628 | 0.710 | 0.242 | 6.827 |
| | | | c | 0.073 | 0.091 | 0.196 | 0.286 | 7.590 |
| | | | d | 1.771 | 1.189 | 1.086 | 0.031 | 3.124 |
| r400_1 | 400 | 8.4 | a | 1.549 | 0.981 | 0.956 | 0.095 | 4.777 |
| | | | b | 0.049 | 0.388 | 0.515 | 0.345 | 15.378 |

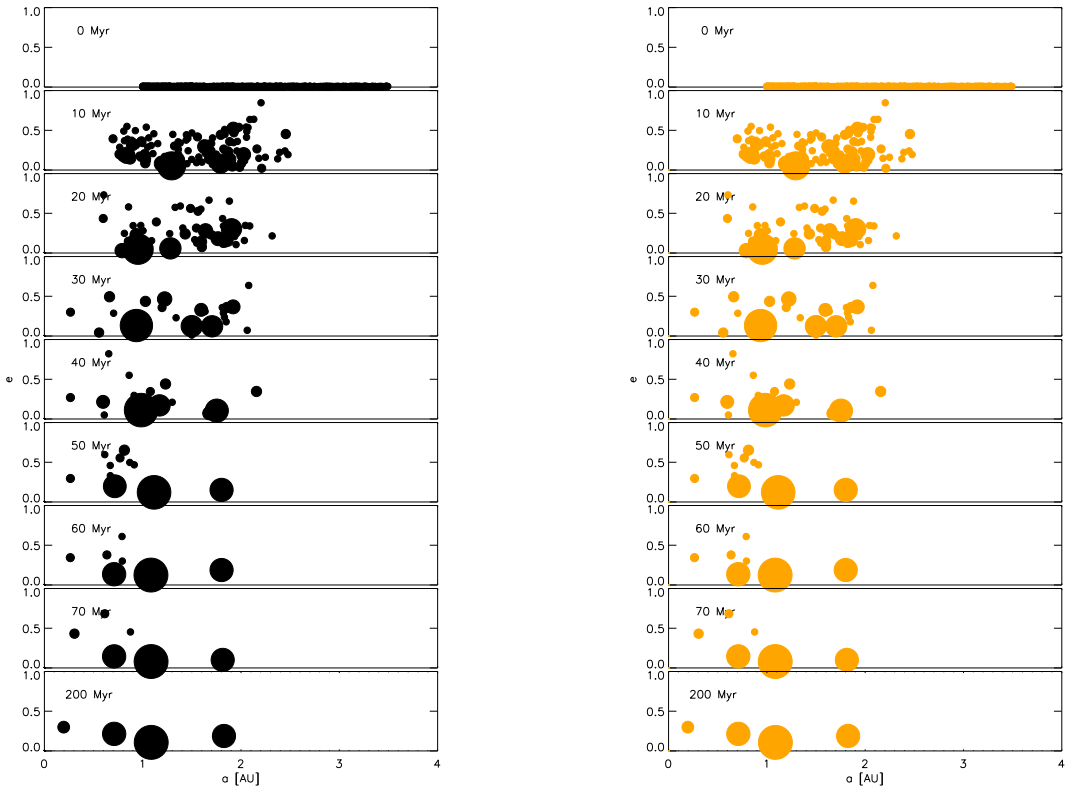


Fig. 1.— Evolution of a circumstellar disk initially populated by lunar-mass planetary embryos in nearly circular orbits around $\alpha$ Centauri B. The radius of each circle is proportional to the size of the object.