PLANETARY FORMATION, RESONANCES, AND STAR MASS ACCRETION IN THE ALPHA CENTAURI SYSTEM.

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We have simulated the last stage of planetary formation in the α Cen binary system. We derive the possible sizes of terrestrial planets that can grow in spite of the gravitational perturbations of the companion star, and the amount of mass of the proto–planetary disk that falls onto the stars. In our simulations we also found a planetary system made of two planets locked in a 2:1 mean motion resonance, confirming that resonant configurations are common in planetary systems.

At present the possible existence of planets around the stars of close binary systems is still matter of debate. Major questions on this topic are: can the gravitational perturbations from the companion star inhibit the accretion of planets? If not, what is the maximum size a planet can reach? During the formation process, do some planetary embryos fall into the stars increasing their metallicity?

We have concentrated on the Alpha Centauri system, the prototype of close binary system with the more massive star very similar to our sun. According to [1], planetesimal accumulation in this system is possible around the primary star thanks to the coupling of two perturbing forces: gas drag and secular perturbations of the companion star. Planetary embryos are likely to form within 2 AU from the star in spite of the strong gravitational disturbance of the companion that, at perihelion, is only ~ 11 AU far from the primary. To compute the outcome of the final stage of planetary formation when large embryos perturb each other in mutually crossing orbits and collide to form planets, we have numerically simulated the evolution of a 3–dimensional disk populated by 100–200 nearly coplanar planetary embryos. The secondary star, α Cen B, is set at 23.4 AU from the primary on an eccentric orbit (e=0.52), all the protoplanets lay in the orbital plane of the binary system and move around the more massive star, α Cen A. The orbits have been integrated with the Mercury package [2] for about 10^8 years. Collisions between embryos are assumed to be completely inelastic.

To compute the initial distribution of embryos around the primary star, we have adopted a surface density of solid material σ equal to 8 $\mathrm{g\,cm^{-2}}$ at 1 AU, and decreasing as $r^{-3/2}$. In the simulations we used different initial values for the embryo's mass ranging from 0.75 M_L ($\sim 0.01 M_\oplus$) to 5.00 M_L ($\sim 0.06 M_\oplus$). The total mass in the embryos was about 75% of that expected in a disk with the above mentioned value of σ and ranged from 1.53 to 2.44 $M_\oplus$, depending on the initial borders of the disk of planetary embryos. The maximum outer edge considered for the disk was 2.79 AU in agreement with the limit for orbital stability of [3], while the inner border was set to 0.4 AU. We assume that not all the mass of the disk is in protoplanets: a sensible fraction possibly remains in small planetesimals. The protoplanets radii are calculated assuming a density of 3 $\mathrm{g\,cm^{-3}}$. The initial eccentricities, e, are randomly selected in the range $0 \leq e \leq 0.04$, the inclinations i in the range $0^\circ \leq i \leq 0.01^\circ$. The remaining orbital elements are chosen randomly between 0° and 360°. We assume that the planetary embryos formed via runaway growth and became dynamically isolated prior the start of our simulation. The initial separation between the planetary embryos, Δ, is measured in mutual Hill radii: we varied the value of Δ from 3 to 9.

Final mass of the planets

In Fig. 1 we show the final mass of the planets that formed in all our 18 simulations as a function of their semimajor axis. The mass values range from 0.2 to 1 $M_\oplus$ and some of them have their orbits within the habitable zone for α Cen A. The final eccentricities are lower than 0.2, some of the planets end up in almost circular orbits. Higher eccentricities are obtained for outer planets where the perturbations of the secondary star are stronger. The inclinations with respect to the binary orbital plane are less than 10°. No planet formed beyond 2.0 AU: the perturbations by the secondary stir up the eccentricities of the bodies in this region and they end up by impacting bodies in the inner zones of the disk.

Infall onto the star and metallicity increase

During the process of planetary formation some embryos, because of the strong perturbations of the binary companion, impact on the primary or on the secondary star. In all our simulations we compute the fraction of the initial mass that ends up in either of the stars, to test if this can lead to some significant difference in the metallicity of the two stars. In Fig. 2 we show the amount of mass plunging into α Cen A and B, respectively. On average, about 5% of an Earth mass goes in either of the stars, so the metallicity of the stars should not have been significantly affected by the planetary accretion process. At least 0.5 $M_\oplus$, according to [4], are needed to alter noticeably the metallicity of a main–sequence star. However, we started our simulations with a protoplanetary disk whose density was equal to that expected in the primordial solar nebula. More massive initial disks would lead to significantly higher amount of mass falling onto the two stars, possibly affecting the composition of the convective envelope. From Fig. 2 we notice that there may be an asymmetry between the two stars in this case, one star gaining more metal rich material than the other.

Resonances

At the end of each simulation we checked the possible existence of mean motion resonances among the planets. In 6 simulations over 18 two planets were close within 1% in semimajor axis to a low order mean motion resonance. In one case we detected the libration of the critical argument of the resonance around 180° (see Fig. 3). The two terrestrial planets are locked in a 2:1 mean motion resonance. This suggests that resonant configurations in planetary systems are not rare.

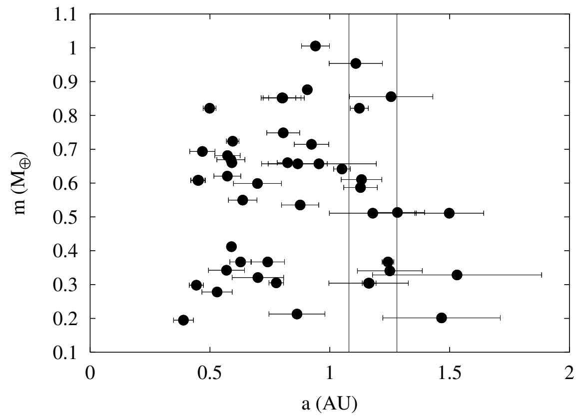

Figure 1: Distribution in semimajor axis and mass of all the terrestrial planets that formed in our simulations of accretion in the α Cen binary system. The vertical lines are the edges of the habitable zone for α Cen A.

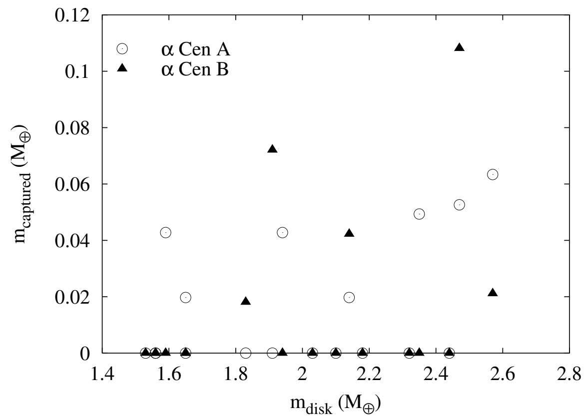

Figure 2: Amount of mass captured by the two stars during the growth of terrestrial planets in α Cen. The horizontal bars show the perihelion–aphelion distances.

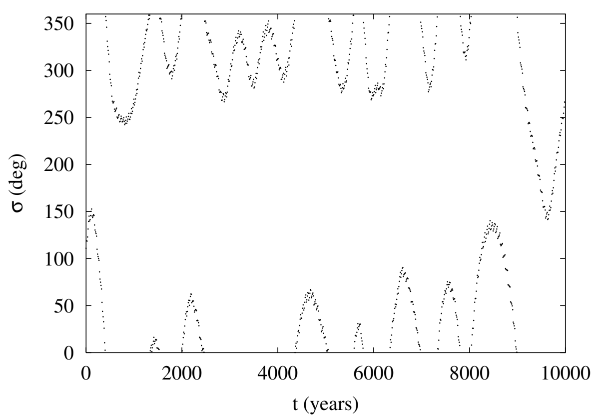

Figure 3: Critical argument $\sigma = 2\lambda_2 - \lambda_1 - \tilde{\omega}_1$ of the 2:1 mean motion resonance detected between two planets at the end of a simulation. λ_1 and $\tilde{\omega}_1$ are the mean longitude and perihelion longitude of the inner planet whose mass is 0.72 $M_\oplus$ and semimajor axis 0.92 AU; λ_2 is the mean longitude of the outer planet whose mass is 0.2 $M_\oplus$ and semimajor axis 1.46 AU.

REFERENCES: [1] Marzari F. and Scholl H., ApJ, 543, 328 (2000). [2] Chambers J., MNRAS, 304, 793 (1999). [3] Holman M. and Wiegert P., AJ, 117, 621 (1999). [4] Murray N. et al. ApJ, 555, 801 (2001).