PLANETARY FORMATION IN THE THE GAMMA CEPHEI SYSTEM BY CORE–ACCRETION. P. Thebault, *Observatoire de Paris, France, philippe.thebault@obspm.fr*, F. Marzari, M. Barbieri, D. Turrini, and V. Vanzani, *Dept. of Physics, University of Padova, Italy*, H. Scholl, *Observatoire de Nice, France*.

Among the presently known binary star systems harbouring extra solar planets, Gamma Cephei is that with the closest companion star. According to [1], the secondary star has an orbit with semimajor axis of 18.5 ± 1.1 AU and an eccentricity of 0.361 ± 0.023. The planet detected around the primary star, a K0 III giant star, has a mass $M sin\ i = 1.7 \pm 0.4$ Jupiter masses and an orbital semimajor axis of 2.13 AU. Within the core–accretion model for giant planet formation [2], the vicinity of the secondary star appears to be critical because 1) it reduces the size of the accretion disk 2) it excites high relative velocities between colliding planetesimals. We analyse via numerical modelling the growth of planetary embryos starting from kilometer-sized planetesimals, and the later stage when large embryos collide to form the core of the giant planet. This last phase precedes that of rapid gas accretion which begins when a substantial mass is accumulated on the core. It is possibly an oversimplification to separate the stages of planetary formation in planetesimal accretion, protoplanet accumulation, and final gas infall. Collisions between embryos start when planetesimal accretion is still going on, and gas trapping begins while the core is still capturing massive planetesimals. However, by modelling separately the different phases, we can at least gain some insights in the major events that characterize each stage. Our modelling of core formation by accumulating massive protoplanets of a few Lunar masses is a sort of intermediate stage between the planetesimal accretion phase and the stage described by models simulating the evolution of the solid core and a gaseous envelope [2].

During the planetesimal phase, accretion is possible when the relative velocities between planetesimals lead to accretion rather than to disruption. The gas drag is known to play a relevant role in this stage [3] by forcing periastron alignment and preventing crossing of orbits with different semimajor axes. Then, the impact velocity is only due to the Keplerian shear and accretion dominates over fragmentation. This effect is critical in particular for binary systems where the companion star, in absence of gas, can dynamically excite the planetesimal population by pumping up significant eccentricities. However, an additional effect of gas drag is to cause a rapid radial infall of planetesimals when they have large eccentricities. In this way, the protoplanetary disk may be depleted of bodies on a short timescale, halting the planet formation. A delicate balancing between planetesimal drift and gas damping of impact velocity must be reached by the system to allow the formation of planetary embryos from small planetesimals.

We have performed several numerical simulations modelling the planetesimal dynamical evolution under the effects of the gravitational pull of the secondary star and gas drag. In order to estimate the relative velocities we use the code already exploited in previous similar studies [4] that enables to follow in a deterministic way the evolution of a swarm of massless particles under the influence of one or several gravitational perturbers and of gas drag. All mutual encounters are tracked and the corresponding relative velocities are computed. We follow the evolution of a swarm of 3000 test planetesimals initially distributed between 0.3-5 AU. The initial eccentricities e and inclinations i are chosen such that $i = e/2$ while the average encounter velocities are $\langle \Delta v \rangle \simeq 10\,\text{m.s}^{-1}$. For the gas density, we take as a reference value at 2 AU the one given by [5], who estimated that the in–situ formation of a giant planet at this distance, requires a gas density of $2\,10^{-9}\text{g.cm}^{-3}$. For the radial profile of this density distribution we take the classical Hayashi prescription: $\rho_g \propto r^{-2.75}$. A series of simulations shows that accretion of planetesimals is possible under this condition within 2.5 AU from the primary star. Fig. 1 presents a typical result of our simulation for a swarm of 10 km size planetesimals.

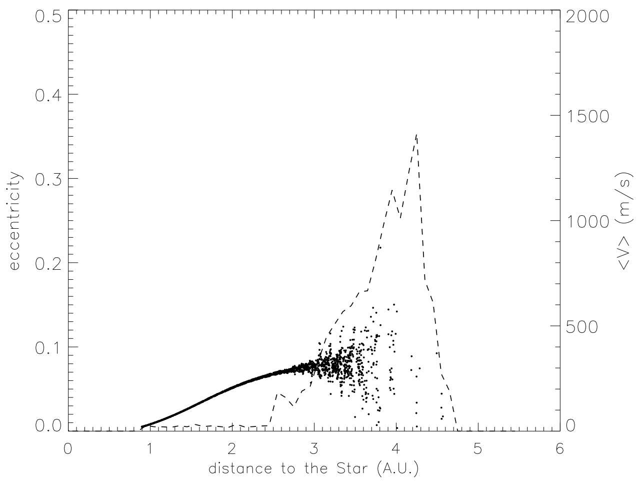

Figure 1: Eccentricity (dots) and mean relative velocity distribution (dashed line) for a swarm of 10 km size planetesimals after 3×10^4 years. Gas drag forces a strong periastron alignment up to about 3 AU: The dots representing eccentricity form a solid line.

Assuming that the planetesimal accretion leads to oligarchic growth of planetary embryos, it is critical to test whether the accretion of protoplanets into a core can occur within 10 Myr (the average lifetime of a gaseous disk) and whether the final giant planet dynamically resembles the observed one. We have simulated, within a full N–body model, the evolution of a population of protoplanets into a massive core by integrating the orbits of a swarm of planetary embryos distributed in between 1 and 2.5 AU where, according to the previous computations, planetesimal accretion is mostly efficient. The orbits of the embryos are computed with Chambers' Mercury code which we modified to account for the large perturbations of the binary companion [6]. The number and initial masses of the embryos are derived assuming a surface density of solid material in the accretion disk around Gamma Cephei ranging from 50 to 100 $g\ cm^{-2}$ at 2.1 AU as in [5]. In all the simulations we assume that only a fraction of the mass of the solids in the disk has accumulated into planetary embryos while the remaining mass is still in smaller planetesimals. This percentage varies from 50% to 75% of the total mass in different models. We also adopted different distributions of the planetary embryos as a function of the distance from the star. At the beginning of the simulation all the embryos have eccentricities lower than 0.04 and inclinations lower than 1° with respect to the orbital plane of the binary system.

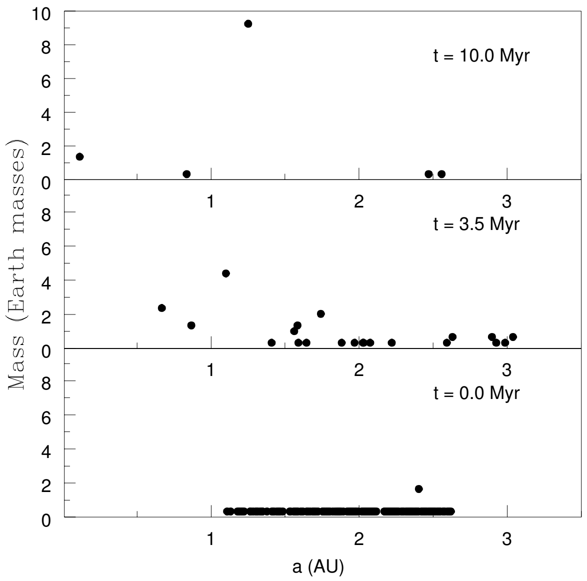

Figure 2: Mass vs. semimajor axis of the embryo population at different times (t = 0., 3.5, 10. Myr).

Our simulations with an initial total embryo mass of 25 $M_\oplus$, about 50% of the solid mass in a disk with $\sigma = 50 gcm^{-2}$, fail to create a core of 10 Earth masses within 10 Myr that is the typical lifetime of circumstellar disks [5]. The maximum mass of the core achieved in these simulations after 10 Myr was 6 terrestrial masses. If we increase the total embryo mass to 35 $M_\oplus$, a core of 8–10 $M_\oplus$ can form in a few cases. All simulations with an initial mass ranging from 50 to 75 $M_\oplus$ lead to the formation of a core with masses up to 20 $M_\oplus$ within 10 Myr. These simulations are compatible with a value of σ around 100 $g\ cm^{-2}$. However, our simulations all show that the core forms always within 1.5 AU from the primary star, while the observed planet is at about 2.15 AU. Even by including in the initial protoplanet population a "proto–core" of 2 Earth masses at 2.15 AU, the final core migrates in between 1 and 1.5 AU. Migration is due to planetesimal scattering reinforced by the gravitational forces exerted by the binary system which excite the embryos' eccentricities.

In Fig. 2 we show the outcome of a simulation with an intermediate value for the total embryo mass (50 $M_\oplus$) and a proto–core initially located at 2.3 AU. The proto–core grows faster than nearby protoplanets but it migrates inward due to the scattering of the other bodies. It settles at about 1.4 AU and its mass reaches almost 10 Earth masses.

How is this then possible to explain the presence of a planet at 2.1 AU within the core–accretion scenario ? First, one cannot exclude that a fast run–away growth of the core prevented the formation of other large embryos. Another possibility is that the binary system was wider when the planet formed and that, some time after the planet formation, additional mechanisms pushed the secondary star on an inner orbit. If the Gamma Cephei system was born in a clustered environment, close encounters with other young stars may cause perturbations of the binary orbit. On average, these perturbations tend to shrink the binary orbit [7]. A different way to reduce the orbit of a binary system is related to the possibility that, originally, the system was triple or more. The ejection of one or more stars causes a transfer of binding energy and an eventual reduction of the binary separation [8]. A more complex mechanism is related to the formation of more than one giant planet around Gamma Cephei. If the circumstellar disk around the main star was significantly more massive with a superficial density of solids higher than 100 gcm^{-2}, it is possible that two or more giant planets formed around the main star. Mutual scattering among these planets ejected one, two or more of them out of the system leaving a single planet in the observed orbit [9][10]. Of course, also alternative mechanism for planet formation based on disk instability [11] can be invoked in this particular case.

REFERENCES: [1] Hatzes A. P., et al., ApJ. 599, 1383 (2003). [2] Pollack J., et al. Icarus 124, 62 (1996). [3] Marzari F., Scholl H., ApJ 543, 328 (2000). [4] Thébault P., Marzari, F., and Scholl, H., A&A, 384, 594 (2002). [5] Bodenheimer P. et al., Icarus, 143, 2 (2000). [6] Chambers J., et al. A.J. 123, 2884 (2002). [7] Heggie, D. C., Dynamics of star clusters, Proc. Symp. Princeton, NJ, May 29,Dordrecht, D. Reidel Publishing Co., 1985, p. 139 [8] Reipurth, B., A.J. 120, 3177 (2000). [9] Weidenschilling, S. J., and Marzari, F., Nature, 384, 619 (1996) [10] Marzari, F., Weidenschilling, S.J., Granata, V., Barbieri, M., LPSC 2004. [11] Boss, A. P., ApJ 551, L167, (2001)