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Exoplanetary formation in S–type binary star systems

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Abstract. In the framework of the ORESTE (ORigin, Evolution and STability of Exoplanets) project we investigated under which assumptions terrestrial and giant planets could form in S–type binary star systems through the processes described by the standard model of planetary formation. We used the systems of α Centauri and γ Cephei as models in our simulations. We studied the possibility of planetesimal accretion and modeled the formation of terrestrial planets (α Centauri case) and of the cores of giant planets (γ Cephei case). Our results show that planetary formation is possible in S–type binary star systems and that the standard model could explain the formation of the observed planets. We also studied the dynamical behaviour of planets in such systems by investigating the stability of their orbits through long term numerical simulations and the FMA (Frequency Map Analysis) method: our results show the dependence of the critical semimajor axis from the orbital inclination and eccentricity.

Key words. Planetary systems: formation, stability, core accretion; stars: binary systems; numerical: N–Body simulations, symplectic mapping, FMA

1. Introduction

The discovery of giant planets orbiting in binary star systems proved that planetary formation is possible in presence of the strong gravitational perturbations of a companion star. In the framework of the **ORESTE (ORigin, Evolution and STability of Exoplanets)** project (Marzari et al. 2003), we investigated under which assumptions terrestrial and giant planets could form in binary systems through the standard model of planetary formation.
We investigated the distribution of collisional relative velocities of planetesimal populations in α Centauri (Marzari & Scholl 2000) and γ Cephei (Thebault et al. 2004) to determine the regions where the relative velocities Δv are low enough to allow accretion of planetesimals. We based on these results to simulate the *giant impacts phase*: we investigated the formation of the terrestrial planets (Barbieri et al. 2002) and of the cores of giant planets (Thebault et al. 2004) by collisional accretion of planetary embryos. We also studied the dinamical stability of planetary orbits through the Frequency Map Analysis method (Laskar et al. 1992).

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2. Numerical codes

To study the accretion process of planetesimals we used a numerical code that computes the orbit of a swarm of massless particles, which can be subjected to gas drag forces, under the influence of one or more gravitational perturbers (Thebault et al. (2002)).
To study the giant impacts phase, we performed full N–Body dynamical simulations using **Mercury 6.2** code (Chambers 1998) with the addition of our **DPI** libraries (Turrini et al. 2004, 2005). The algorithm we used for the stability analisys is based on the Frequency Map Analysis (FMA) method developed by Laskar et al. (1992) and is part of the **ORSA** software, which can be found and downloaded at `http://orsa.sourceforge.net`.

3. Planetesimal accretion

The vicinity of a companion star may prevent the formation of the terrestrial planets and of the cores of the giants planets because the companion star reduces the size of the accretion disk and could excites high relative velocities between colliding bodies. The relative impact velocity Δv determines whether accretion or erosion dominates the collisional evolution.
We simulated for 10^5 years the orbital evolution of several swarms of massless particles placed inside the stability regions of the two systems (Holman & Wiegert 1999).The gas and dust density values matched the ones inferred for the minimum mass solar nebula (MMSN) for the α Centaury case and were an order of magnitude greater for the γ Cephei case (Bodenheimer et al. 2000).

4. Giant impacts phase and planetary formation

To study the formation of terrestrial planets in the α Centauri system we generated the initial conditions assuming the embryos swarms composed of 200 bodies of lunar mass and size (Barbieri et al. 2002). The simulations lasted 10^8 years. While studying the cores formation in γ Cephei we also investigated how the planetary formation process responds to variations of the initial mass distribution of the solid component, using different dust density profiles and dust superficial density values (Thebault et al. 2004). These simulations lasted 10^7 years (Thebault et al. 2004).
Collisions between embryos were assumed to be completely inelastic: fragmentation or cratering were not considered. This approximations holds since the gravitational binding energy for large bodies overcomes the kinetic energy of the fragments even for high velocity impacts.

5. Stability analysis with the FMA method

We investigated the dynamical stability of the γ Cephei's giant planet by using the FMA method (Laskar et al. 1992). We analysed the stability of the system by varying in a continuos way the initial semimajor axis and orbital eccentricity of the giant planet. Our results (see fig. 1 and Turrini et al. (2004, 2005)) are in good agreement with the ones present in literature (Holman & Wiegert 1999).

6. Conclusions

The results of our studies of the accretion of planetesimals in α Centauri and in γ Cephei show that this process depends on a delicate balancing between gas drag and secular perturbations by the secondary star. This balancing causes a strong alignment of the periastra of the orbits of planetesimals, thus reducing the encounter velocities Δv in spite of large eccentricities (Marzari & Scholl (2000), Thebault et al. (2004) for reference).
The accretion of terrestrial planets is possible in α Centauri under the hypothesis of a protoplanetary disk comparable to the MMSN (Barbieri et al. 2002). In the γ Cephei case giant planets could form under the assumpion of a protoplanetary disk an order of magnitude more massive than the MMSN (Thebault et al. 2004; Turrini et al. 2004, 2005). Our results show a correlation between the fraction of critical cores, their final masses, their formation times and the total mass initially incorporated in the embryos swarms (see table 1 and Turrini

Swarm Mass ($M_\oplus$)	Dust superficial density ($g\,cm^{-2}$)	Fraction of formed cores	Formation percent	Formation time scale
25	50	0/8	0%	> 10 Myrs
35	50	3/8	37.5%	8–10 Myrs
45	100	6/8	75%	4–6 Myrs
75	100	8/8	100%	1–2 Myrs

Table 1. : Summary of the results of the N-body simulations of the giant impacts phase in γ Cephei.

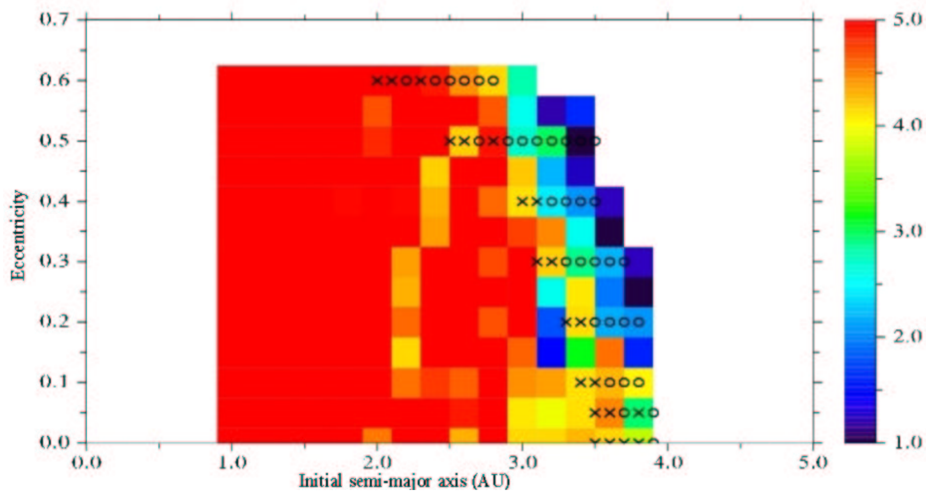

Fig. 1. : In this figure we represent the dynamical stability of the giant planet in γ Cephei, with semi–major axis on the x axis and the eccentricity on the y axis, as resulting from the FMA. The color scale represent the diffusion velocity in the phase space and goes from blue for the chaotic regions to red for the stable ones (see Turrini et al. (2004, 2005)).

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We also found that the final semimajor axis of the critical core is very sensitive to the mass distribution and that radial migration is very likely to take place during its formation (Thebault et al. 2004; Turrini et al. 2004, 2005).

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