Mem. S.A.It. Suppl. Vol. 6, 172

Memorie della
Supplementi

Planetary Formation and Orbital Stability in Binary Star Systems

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Abstract. Among the presently known extrasolar planetary systems, almost 20 are in binary star systems but their orbital parameters are far different from those predicted by the standard model of planetary formation. In our work we investigated under which assumptions terrestrial and giant planets could form in such complex dynamical environments, using 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 binary star systems and that the standard model could explain the formation of the observed planets. We studied the dynamical stability of planetary orbits in γ Cephei by using the FMA 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 even 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 system through the processes described by the standard model of planetary formation.
In the first part of our work we investigated the distribution of collisional relative velocities of planetesimal populations in α Centauri (Marzari & Scholl 2000) and γ Cephei (Thebault et al. 2004): these studies are intended to determine the regions where the relative velocities Δv are low enough to allow accretion of planetesimals and to estimate the effects of the companion star and of the dissipative processes like gas drag in changing the value of Δv. We then based on the results of this study to generate the input data and initial conditions for the second part of the work, in which we simulated the latest stage of planetary formation, the *giant impacts phase*: we investigated the formation of the terrestrial planets (Barbieri et al. 2002) and of the cores of gi-

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ant planets (Thebault et al. 2004) by collisional accretion of planetary embryos of lunar mass and size. In the last part of our work, we studied the dinamical stability of planetary orbits through the use of the Frequency Map Analysis method (Laskar et al. 1992): we sampled the orbital region between 1 and 4 AU from the primary star with various values of initial eccentricity and inclination, in order to allow the evaluation of their effects on the dinamical stability of the planet (Turrini et al. 2004).
The present work is divided into the following sections:

- in section 2 we describe the numerical codes we used in our simulations;
- in section 3 we describe the results of our studies of the distribution of the relative velocities among planetesimals in the two systems we modeled;
- in section 4 we descrive the results of the modeling of the giant impacts phase and the conditions necessary to form terrestrial and giant planets;
- in section 5 we analyse the dynamical stability in the γ Cephei system and the reliability of the FMA method:
- in section 6 we discuss the results of our investigations.

2. Numerical codes

In the first part of the work, 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) and references therein). Using this code we can reconstruct the distribution of the impact velocities during planetesimal collisions and determine where accretion is possible.
In the second part of the work, to study the giant impacts phase, we performed full N–Body dynamical simulations: to compute the orbital evolution of the systems and the collisions between the bodies we used **Mercury 6.2** code (Chambers 1998) with the addition of our **DPI** libraries (Turrini et al. 2004). DPI is a set of Fortran77 subroutines we developed as a plug–in for the Mercury software in order to use the symplectic mappings for the binary star systems (Chambers et al. 2002). We tested the reliability of our implementation by comparing the results of the test simulations done by Chambers et al. (2002) with the ones produced by our code. We also compared the output of our simulations for the stability study with the ones computed with the HJS algorithm by Beust (2003). DPI libraries are freely obtainable by writing to the author at his e–mail address: the new version including the P type binary systems will be released soon.
The algorithm we used in the last part of our work, 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 is a critical parameter for the initial stage of planetesimal accretion. This quantity determines whether accretion or erosion dominates the planetesimal collisional evolution: if large Δv values occur, planetesimals cannot accrete and the initial population may be grounded down to dust.
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). We performed two different sets of simulations: in the first one we didn't include gas drag forces while in the second one we included them, in order to evaluate their effects on the distribution of the encounter velocities. 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

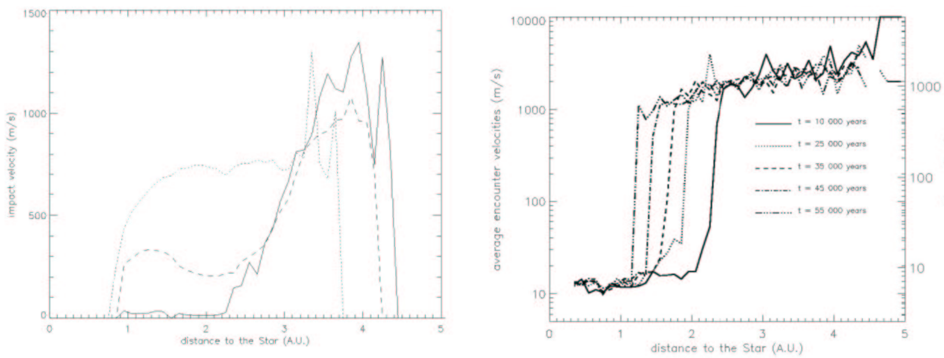

Fig. 1. : The graph on the left represents the evolution of the encounter velocity with semimajor axis at 5 different epochs for the model without gas drag. The solid line in the graph on the right shows the encounter velocities in the model with gas drag: the presence of the gas damps the encounter velocities allowing the accretion of the planetary embryos.

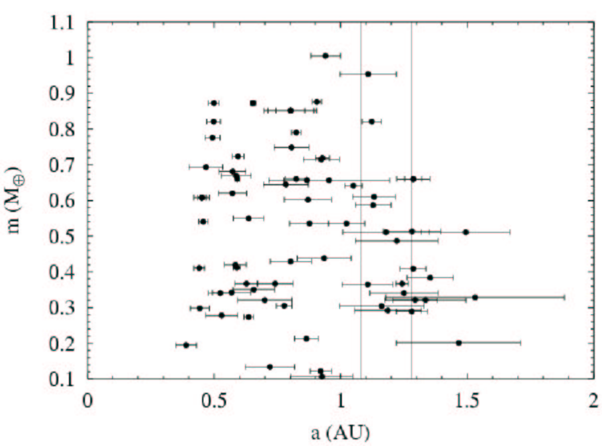

Fig. 2. : This graph represents the output of the N-Body simulations, showing the distribution of semimajor axis vs. mass for the terrestrial planet which formed. The vertical lines represents the boundaries of the habitable zone in α Centauri, while the horizontal bars show the perihelion-aphelion distances of each planet.

of magnitude greater for the γ Cephei case (Bodenheimer et al. 2000).

4. Giant impacts phase and planetary formation

In the second part of the work, to study the formation of terrestrial planets in the α Centauri system we generated the initial conditions starting from the results of the previous simulations, assuming the embryos swarms composed of 200 bodies of lunar mass and size (Barbieri et al. 2002). The simulations lasted 10^8 years.

In studying of 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. We considered different dust density profiles and dust superficial density values (Turrini et al.

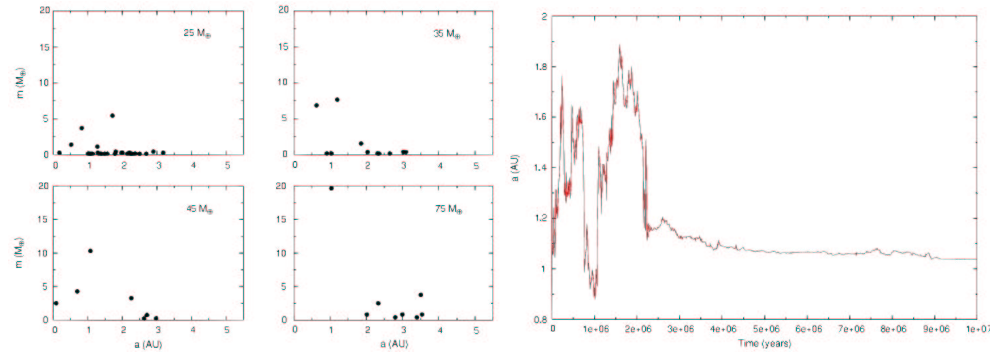

Fig. 3. : Each graph of the left hand figure represent the typical situation at the end of a simulation with a specific value of the initial mass of the embryos swarm. The right hand figure shows the radial migration of a core during the accretion process.

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

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

2004). This variation reflected on the spacing between the embryos composing the swarms, which we assumed composed of 150 bodies with mass ranging from lunar to martian values. The timespan of the simulations has been chosen equal to the maximum lifetime of the gaseous component of a protoplanetary disk, about 10^7 years.

In our simulations, 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, originally developed by Laskar et al. (1992) to study the minor bodies of the Solar System: this method permits to study the long term behaviour of dynamical systems by integrating them over very limited timespan. We analysed the stability of the system by varying in a continuos way the initial semimajor axis and orbital eccentricity of the giant planet. We also checked the validity of the FMA on the edge of the stability region by comparing its results with the ones of a set of long term numerical simulations (Turrini et al. 2004). Our results (see Fig. 4) are in good agreement with the ones present in literature (Holman & Wiegert 1999) and they also agree with the numerical simulations we did close to the boundary of the stability zone (see Fig. 4), thus confirming the reliability of the FMA method in such dynamical scenarios.

6. Conclusions

The results of our studies of the accretion of planetesimals in the disks of α Centauri and of γ Cephei show that this process depends on a

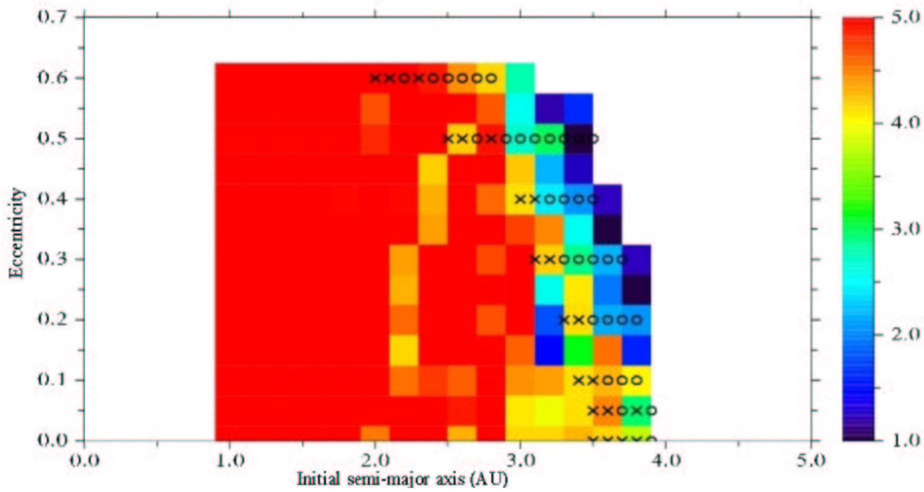

Fig. 4. : In this figure we represent the dynamical stability of the giant planet in γ Cephei, with semi–major axis on the x axis and the eccentricity on the y axis, as resulting from the FMA. The color scale represent the diffusion velocity in the phase space and goes from blue for the chaotic regions to red for the stable ones. The X and O symbols represent the results (respectively stable and chaotic orbits) of the numerical integration we did close to the boundary of the stable region with HJS and DPI.

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 (see Fig. 1 and Marzari & Scholl (2000), Thebault et al. (2004) for reference).

Our results in the modeling of planetary formation show that the accretion of terrestrial planets is possible in the α Centauri system under the hypothesis of a protoplanetary disk comparable to the MMSN (Barbieri et al. 2002). In our simulations planets of the size of Mars and Venus do form (see Fig. 2): they are typically on low eccentricity orbits and are stable over the age of the system. Some of these planets form in the habitable zone of α Centauri (see Fig. 2).

Similar results are obtained from the simulations in the γ Cephei case: giant planets formation is possible under the assumpion of a protoplanetary disk an order of magnitude more massive than the MMSN (Thebault et al. 2004; Turrini et al. 2004). The results of our simulations show a straightforward correlation between the fraction of cores reaching the critical mass, the final masses of the cores, the time necessary to reach the critical mass (about $10 M_\oplus$) and the total mass initially incorporated in the embryos swarms (see Table 1 and the left hand graph of Fig. 3).

We also found that the final semimajor axis of the critical core is very sensitive to the mass distribution (Thebault et al. 2004; Turrini et al. 2004). For density profiles different from the one assumed for the MMSN, the cores never form at the observed distance (2 AU). They usually form at about 1 AU from the star and in the case the cores initially form at the right distance, the gravitational scattering with lesser bodies causes them to migrate radially to more internal orbits (see the right hand graph of Fig. 3).

References

Barbieri M., Marzari F., & Scholl H., 2002, A&A, 396, 219

Beust H., 2003, A&A 440, 1129-1144

Bodenheimer P., Hubickyj O., & Lissauer J. J., 2000, Icarus, 143, 2-14

Chambers J.E., 1998, MNRAS 000, 1-8

Chambers J. E., Quintana E. V., Duncan M. J., & Lissauer J. J., 2002, ApJ, 123, 2884-2894

Holman M. J., & Wiegert P. A., 1999, AJ, 117, 621-628

Laskar J., Froeschlé C. & Celletti A., 1992, Physica D 56, 253-269

Marzari F. & Scholl H., 2000, ApJ, 543, 328

Marzari F., Thebault P., Scholl H., & Turrini D., 2003, AAS, DPS 35

Thebault P., Marzari F., & Scholl H., 2002, A&A, 384, 594

Thebault P., Marzari F., Scholl H., Turrini D., & Barbieri M., 2004, A&A, 427, 1097

Turrini D., Barbieri M., Marzari F., & Tricarico P., 2004, MSAIS, 5, 127