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Planetary formation in the γ Cephei system

P. Thébault[1], F. Marzari[2], H. Scholl[3], D. Turrini[2], and M. Barbieri[1,2]

[1] Observatoire de Paris, Section de Meudon, 92195 Meudon Cedex, France
e-mail: philippe.thebault@obspm.fr
[2] Dipartimento di Fisica, Universita di Padova, via Marzolo 8, 35131 Padova, Italy
[3] Observatoire de la Côte d'Azur, Dept. Cassiopée, BP 4229, 06304 Nice, France

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Abstract. We numerically investigate under which conditions the planet detected at 2.1 AU from γ Cephei could form through the core-accretion scenario despite the perturbing presence of the highly eccentric companion star. We first show that the initial stage of runaway accretion of kilometer-sized planetesimals is possible within 2.5 AU from the central star only if large amounts of gas are present. In this case, gaseous friction induces periastron alignment of the orbits which reduces the otherwise high mutual impact velocities due to the companion's secular perturbations. The following stage of mutual accretion of large embryos is also modeled. According to our simulations, the giant impacts among the embryos always lead to a core of 10 $M_\oplus$ within 10 Myr, the average lifetime of gaseous discs. However, the core always ends up within 1.5 AU from the central star. Either the core grows more quickly in the inner region of the disc, or it migrates inside by scattering the residual embryos.

Key words. planets and satellites: formation – stars: binaries: general

1. Introduction

Among the 15 presently known binary star systems harbouring extra-solar planets, γ Cephei is that with the closest companion star (with the exception of Gliese 86, where the possible companion is believed to be a brown dwarf, Els et al. 2001). According to Hatzes et al. (2003), the secondary star has an orbit with a semimajor axis of 18.5 ± 1.1 AU and an eccentricity of 0.361 ± 0.023. The planet detected around the primary K0 III giant star has a mass of $M \sin\ i = 1.7 \pm 0.4$ Jupiter masses and an orbital semimajor axis of 2.13 AU. The planet is located inside a stable region with a dynamical lifetime of at least 1 Gyr. This region extends to about 4 AU from the central star (Holman & Wiegert 1999; Dvorak et al. 2003).

Giant planets orbiting one of the stars in a binary system offer the possibility to test the core-accretion model for giant planet formation (Pollack et al. 1996) in a complex dynamical environment. The vicinity of a companion star in a highly eccentric orbit may prevent planetary formation because the companion reduces the size of the accretion disc, and it excites high relative velocities between colliding planetesimals.

In this paper we study the in situ formation of the giant planet in the γ Cephei system by numerically investigating both the stage of planetary embryo accretion from planetesimals and the following stage of high velocity collisions between large embryos which form the core of the giant planet. This last stage precedes that of rapid gas accretion which sets on after sufficient accumulation of mass onto the core.

A critical parameter for the initial stage of planetesimal accretion is the *relative impact velocity* Δv. This velocity determines whether accretion or erosion dominates the planetesimal collisional evolution. In a binary star system, the secular perturbations of the closeby companion star may play a critical role by exciting the relative velocities among the planetesimals. Too large Δv prevent planetesimals from growing by accretion and the initial planetesimal population may even be ground down to dust. We explored the distribution of collisional relative velocities of a planetesimal population surrounding the primary star of the γ Cephei system by using a deterministic code that includes the effect of gas drag. This latter mechanism might indeed play a crucial role since gas drag might force periastron and eccentricity alignment of the perturbed planetesimal orbits and thus reduce the large Δv induced by the companion's perturbations (e.g. Marzari & Scholl 2000).

We also investigated the late stage of core formation by following a population of large planetary embryos with a numerical model based on Chambers' Mercury code (Chambers et al. 2002) which takes into account all mutual gravitational forces among the embryos as well as mutual collisions. Our main concern is here to see if mutual accretion of embryos can lead to a final planet at the right place, i.e. ≃2.1 AU, and within 10^7 years, i.e. the typical survival time for circumstellar discs (e.g. Armitage et al. 2003).

The dynamical conditions for accretion within a planetesimal swarm perturbed by the companion of γ Cephei and affected by gas drag are investigated in Sect. 2. Section 3 is

devoted to the study of the final accumulation of massive embryos into a core. In Sect. 4 we discuss the results.

2. Relative velocities among planetesimals

Planetesimal accretion in a circumstellar disc occurs when mutual encounter velocities are lower than the escape velocity $V_{\rm esc}$ of the mutually colliding bodies (corrected by a factor that accounts for the energy dissipation in the impact). In the absence of external perturbations, average eccentricities and inclinations in a planetesimal swarm are small, and relative velocities are always low enough to allow fast runaway accretion of larger bodies on timescales of the order of 10^4–10^5 years (e.g. Lissauer 1993). When the planetesimal population surrounds a star in a binary system, the gravitational pull of the companion star excites large eccentricities and the impact velocities may in some regions exceed by far the mutual escape velocity. In these regions the swarm would erode to dust rather than form a planet.

A first step to test whether planetary formation is possible around γ Cephei is thus to estimate the relative velocities between planetesimals orbiting within the dynamically stable region around the star. We have used a numerical code already adopted in similar studies (see Thébault et al. 2002, and references therein). This code computes the orbits of a swarm of massless particles under the influence of one (or several) gravitational perturbers. The particles can also be subjected to gas drag forces. During the orbital computations, the relative velocities of all mutual encounters are recorded. These velocities approximate with a satisfying degree of precision the impact velocities during planetesimal collisions. Their distribution tells us whether planetesimals accrete into larger bodies or erode into smaller pieces.

In all our simulations we integrate the orbits of 2500 test particles initially distributed in the 0.3–5 AU region. The initial eccentricities and inclinations satisfy the relation $i = e/2$ and are chosen such that the average encounter velocity is $\langle \Delta v \rangle \simeq 10\,{\rm m\,s^{-1}}$. We stop our simulations after $t_{\rm final} = 10^5$ years, a typical timescale for the formation of planetary embryos (Lissauer 1993).

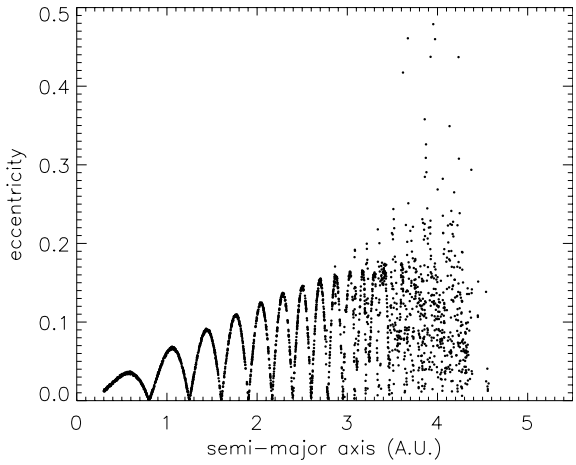

Fig. 1. Distribution of particle eccentricity vs. semimajor axis after $t = 50\,000$ years for a simulation where the gas drag is not included.

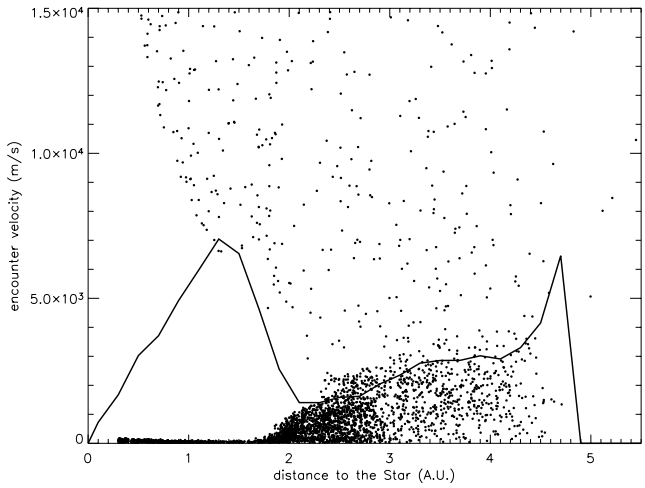

Fig. 2. Plot of Δv vs. radial distance to the star of the planetesimal swarm at $t = 50\,000$ years. Each dot stands for an encounter that has occurred at a velocity Δv and at a distance r from the star during $[t - 10^4, t + 10^4]$. The continuous line is the average encounter velocity at each distance from the star.

2.1. Gravitational model without gas drag

We performed a first test simulation where only the gravitational forces of the two stars are taken into account. Figure 1 shows the major secular perturbations of the companion star on the planetesimal population. At the beginning of the simulation eccentricities progressively increase but the periastra of these forced orbits are almost aligned. As time goes on, however, there is a progressive dephasing process due to the different values of semimajor axis of the planetesimals in the swarm. This dephasing leads to the wavy pattern observed in Fig. 1. The planetesimals orbiting close to the outer limit of the disc at $\simeq$4.5 AU are more strongly perturbed by the secondary star and they reach very high eccentricities. They also survive over 10^5 years and they cross the orbits of inner planetesimals in the 0–3 AU region at high Δv (hence the wide "wing" of high Δv that is superimposed on the main swarm of lower relative velocities in Fig. 2). The contribution of these scattered planetesimals is critical since they increase relative velocities far beyond the accumulation threshold everywhere in the inner disc. However, it is a matter of debate whether planetesimals could indeed form in the outer edge of the stability region around the primary star. Moreover, theoretical calculations of binary–disc interactions predict that companions might truncate circumstellar discs at an outer radius of 0.2–0.5 times the binary semimajor axes (Artymowicz & Lubow 1994). The grain coagulation process and the first impacts between the proto–planetesimals would in any case have been highly energetic, because of the companion's perturbations, possibly halting any further growth. For this reason, we performed an additional simulation with the planetesimal disc truncated beyond 4 AU. In Fig. 3 we show the distribution of the impact velocities at different evolutionary times in this truncated disc. At the beginning, the secular oscillations do not induce a

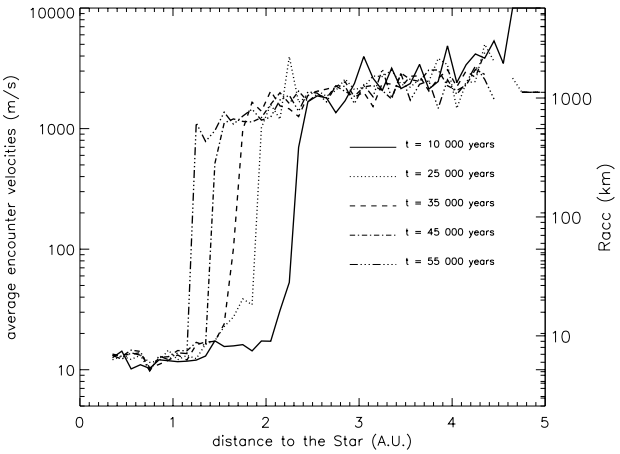

Fig. 3. Evolution of the average encounter velocity distribution, at 5 different epochs, for the gravitational model without gas drag in a disc initially truncated at 4 AU. $R_{\rm acc}$ is the size of the smallest body that can accrete matter, after a collision with an equal-sized object, for a given encounter velocity Δv. It is given by $R_{\rm acc} = f\left(\frac{3}{8\pi\rho_{\rm p}G}\right)^{0.5}\Delta v$, where $\rho_{\rm p} = 3\,{\rm g\,cm^{-3}}$ is the density of the body and f is a coefficient taking into account the energy dissipation in an impact. We adopt here the usual assumption that 90% of the energy is dissipated in the radial direction (e.g. Petit & Farinella 1993) which leads to $\langle f\rangle \simeq 0.7$.

significant increase of Δv among planetesimals because of the strong phasing of all neighbouring orbits. Nevertheless, the oscillations get narrower with time, and e and periastron ω gradients between adjacent regions keep increasing. At some point the orbital phasing is no longer strong enough to prevent orbital crossing between bodies with different semimajor axis. The inner limit for the region where orbit crossing occurs is very sharp, with $\langle\Delta v\rangle$ increasing from $10\,{\rm m\,s^{-1}}$ to $\simeq 1\,{\rm km\,s^{-1}}$ in less than 0.2 AU (Fig. 3). Furthermore, this limit evolves inwards with time, so that the 2.1 AU region is reached in less than 1.5×10^4 years (Fig. 3). As a consequence, the timespan during which accretion of km-sized objects is possible within 2.1 AU from the star, assuming that the swarm was initially aligned, is typically of the order of 10^4 years. Numerical accretion models predict that this time span is in principle enough to allow the formation of 100 to 1000 km-sized bodies (e.g. Wetherill & Stewart 1993; Barge & Pellat 1993; Weidenschilling et al. 1997). However, the large relative velocities that build up after 10^4 years might halt any further growth of the accreted objects. It is even possible that the planetesimal formation process from the dust of the circumstellar disc does not necessarily lead to orbits that are initially aligned. In this case, the planetesimals would have high relative velocities from the beginning of their evolution. This might be the case if we suppose that the binary forms by direct stellar-like gravitational instabilities. The companion star would reach its present mass well before the onset of planetesimal accretion in the inner disc. Thus, the formation of large embryos in the 2 AU region probably requires the presence of some additional mechanism.

2.2. The effects of gas drag

Frictional drag by the gas of the protoplanetary disc is an important factor in early planetary formation. It affects planetesimal orbits in two ways:

- It restores the periastron alignment (Marzari & Scholl 2000), preventing orbital crossing of orbits with different semimajor axes. At the same time, it partially damps the amplitude of oscillations in eccentricity induced by the companion star.
- It causes a drift towards the central star that is particularly fast for planetesimals in binary star systems: the forced component in the planetesimal eccentricity is large, in spite of the damping effect, and it causes a fast drift towards the star.

Following Weidenschilling & Davis (1985), we model the gas drag force as:

$$\boldsymbol{F} = -Kv\boldsymbol{v} \tag{1}$$

where $\boldsymbol{F}$ is the force per unit mass, $\boldsymbol{v}$ the velocity of the planetesimal with respect to the gas, v the velocity modulus, and K is the drag parameter. It is a function of the physical parameter of the system and is defined as:

$$K = \frac{3\rho_{\rm g}C_{\rm d}}{8\rho_{\rm pl}R_{\rm pl}} \tag{2}$$

where $\rho_{\rm g}$ is the gas density, $\rho_{\rm pl}$ and $R_{\rm pl}$ the planetesimal density and radius, respectively. $C_{\rm d}$ is a dimensionless coefficient related to the shape of the body ($\simeq$0.4 for spherical bodies). As appears from the expression of the parameter K, the relevance of the drag force on the dynamics of the planetesimals depends on the ratio between the gas density and the planetesimal size. As a consequence, the results we obtain for a particular value of $\rho_{\rm g}$ and $R_{\rm pl}$ can be extended to different combinations of the two parameters without any additional simulation.

We take as a reference value for the gas density that of Bodenheimer et al. (2000) who modeled the in situ formation of a giant planet around 47 UMa at 2 AU. Of course, the two systems are not exactly comparable, the planet around 47 UMa being $\simeq$50% more massive whereas the star is $\simeq$60% less massive. While these two values might compensate one another it is difficult to quantitatively estimate how much exactly. However, the Bodenheimer et al. (2000) study gives a good reference value for the in-situ formation of a giant planet in an inner orbit. According to these authors, this formation requires a local gas density $\rho_{\rm g(2\ AU)} = 2\times10^{-9}\,{\rm g\,cm^{-3}}$, about an order of magnitude higher than the value deduced from the Hayashi (1981) minimum mass solar nebula. We here use this value for $\rho_{\rm g(2\ AU)}$ and adopt the classical $\rho_{\rm g} \propto r^{-2.75}$ radial profile of Hayashi (1981). Different values of $R_{\rm pl}$ are taken in independent simulations to explore the parameter space. The initial parameters adopted for our reference runs are summarized in Table 1.

For planetesimal accretion to occur, a balance between different competing mechanisms is needed. For too small planetesimals, there is the risk that a too strong gaseous friction leads to a fast inward drift that prevents accretion of larger bodies far from the star. This is illustrated in Fig. 4: a population

Table 1. Initial parameters for the reference gas drag runs.

Number of bodies	2500
Physical radius of bodies	variable (see graphs)
Initial semi-major axis	0.3–5 AU
Initial eccentricities	$0 < e < 10^{-3}$
Initial inclinations	$0 < i < 5.10^{-4}$ rd
Gas density at 2 AU	$\rho_{g0} = 2 \times 10^{-9}$ g cm^{-3}
Gas density radial profile	$\rho_g \propto r^{-2.75}$

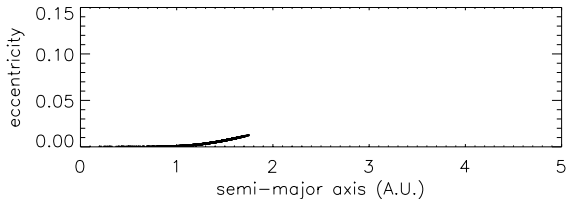

Fig. 4. Eccentricities vs. semi-major axis at $t = 2500$ years for 200 m-sized planetesimals. The gas density is taken from Bodenheimer et al. (2000) with a nominal Hayashi (1981) radial profile.

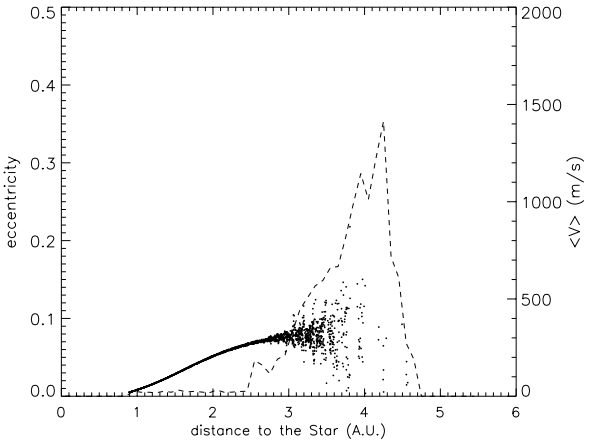

Fig. 5. Eccentricity vs. semimajor axis plot after $t = 50\,000$ years for 10 km-sized planetesimals. The dashed line is the corresponding average encounter velocity distribution as a function of the distance to the star. Gas density is the same as in Fig. 4.

of 200 m-sized bodies migrates towards the star in less than 2×10^3 years, leaving the region beyond 2 AU totally depleted of material. On the other hand, large planetesimals, that are less affected by gas drag, do not significantly migrate but their periastron alignment is weaker. If it gets too weak, then encounter velocities may not be reduced below the value that allows accretion into larger bodies.

In between these two accretion-inhibiting cases, there is a planetesimal size-range where periastron alignment and eccentricity damping are efficient enough to reach very low Δv without removing bodies from the system on a short timescale. As an example, for 10 km bodies the periastron alignment keeps the impact velocities below 10 m s^{-1} within 2.5 AU from the star (Fig. 5) and the drift rate is also slow enough not to deplete this region of the disc within 10^5 years. Figure 6 shows the limiting case, i.e. the run with the biggest R_{pl} (50 km) in which accretion is still possible at 2.1 AU. Beyond 2.2 AU the

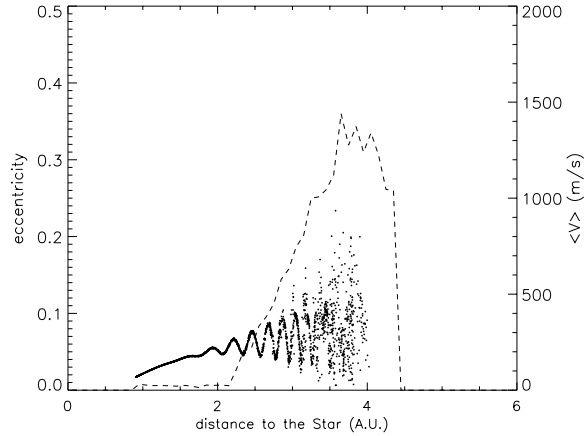

Fig. 6. Same as Fig. 5 but for 50 km-sized bodies.

collision velocities begin to grow quickly as the secular perturbations are dephased.

As the planetesimal accretion proceeds, larger bodies are formed and they still collide with the smaller ones that possibly still make up most of the mass of the swarm. It is relevant to verify whether the impact velocities between large and small planetesimals still favour accretion rather than fragmentation. The perihelion alignment is indeed different depending on the size of the body. Smaller bodies tend to align their perihelia towards 270° (Marzari & Scholl 2000) while larger planetesimals, less affected by the drag force, align to larger values. At the orbital crossing the impact velocities may thus be higher compared to those of equal-size bodies. We performed additional simulations where we include different size planetesimals. Figure 7 shows the relative velocities between populations of different size planetesimals. For 50 km target objects, colliding speeds significantly increase when the impactor sizes get smaller, especially in the otherwise low Δv region below 2.5 AU. The Δv might reach $\simeq$300 m s^{-1} when 10 km impactors are considered, and even $\simeq$700 m s^{-1} for 1 km objects. However, it can be shown that such impact velocities still lead to accretion. Adopting the collisional algorithm described in Petit & Farinella (1993), we find that a collision between a 50 km and a 10 km object at 300 m s^{-1} leads to net accretion of $\simeq$85% of the impactor's mass, and that a collision between a 50 km and a 1 km object at 700 m s^{-1} leads to net accretion of $\simeq$95% of the impactor's mass.

Conditions slightly more favourable to planetary formation, i.e. allowing accretion of objects bigger than 50 km, are met if we adopt a flatter gas density profile or if we truncate the disc closer to the star. In Fig. 8 we show the relative velocity distribution in a disc of 50 km radius planetesimals cut at 3 AU from the central star and a gas density profile in $r^{-1.5}$ giving a stronger drag force between 2 and 3 AU. Additional simulations show that under these conditions low Δv are maintained for bodies up to $\simeq$200 km, while the inner limit of the low Δv region never extends beyond 2.5 AU.

For bodies in the 200–1000 km range, higher Δv are obtained in the $a < 2.5$ AU region, especially for collisions with smaller planetesimals, which are probably the most frequent impactors on these bigger objects (Fig. 9). However, such

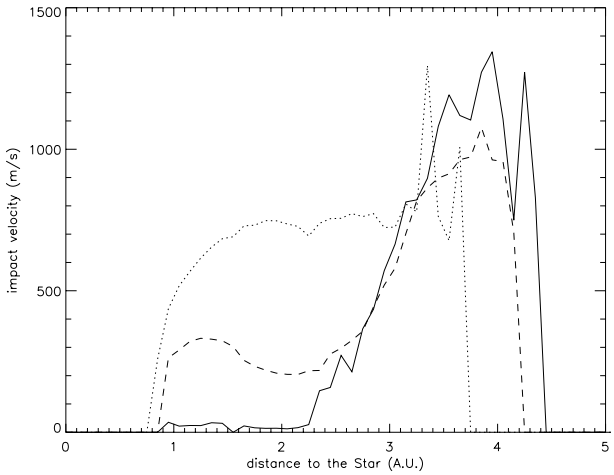

Fig. 7. Mutual relative velocities, at $t = 30\,000$ years, for a disc with 3 different populations of objects: 1 km, 10 km and 50 km in sizes. The solid line stands for Δv among 50 km bodies, the dashed line for Δv between 50 km and 10 km bodies and the dotted line for Δv between 50 km and 1 km bodies. The gas disc has the same characteristics as in Figs. 4–6.

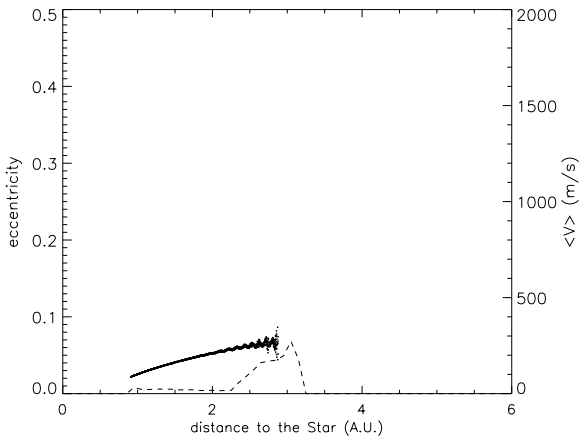

Fig. 8. Same as Fig. 6 (50 km bodies at $t = 50\,000$ years) for a planetesimal disc initially truncated at 3 AU. The gas density decreases radially as $r^{-1.5}$.

high Δv impacts still lead to net mass accretion. Using again the Petit & Farinella (1993) algorithm for velocities obtained on a 500 km target (Fig. 9), one gets that 95% of the impactor's mass is reaccreted after a 1200 m s^{-1} collision with a 50 km impactor, 97% for a 1400 m s^{-1} impact with a 10 km body and 98% for a 1700 m s^{-1} collision with a 1 km impactor. So even considering the large uncertainties in collision and reaccretion physics, it seems that we are far below the accretion threshold for 500 km bodies in our "extreme" gas disc case, i.e. high gas density in the outer regions (flat radial distribution) and cut-off at 3 AU for the planetesimal swarm.

Furthermore, even with lower gas densities, the final accretion phase of objects in the 200–1000 km range can be favoured by additional mechanisms that cannot be taken into account in our N-body simulations. Dynamical friction produced by the gravitational interactions between planetesimals tends to produce equipartition of energy (Wetherill & Stewart 1989). As a consequence, larger bodies have lower random

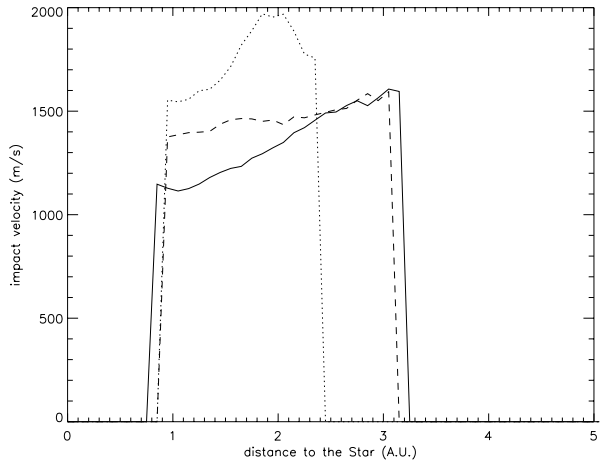

Fig. 9. Impact velocities, at $t = 15\,000$ years, on 500 km bodies for 50 km (continuous line), 10 km (dased line) and 1 km (dotted line) impactors. Same high density truncated disc as in Fig. 8. The absence of ΔV values beyond 2.5 AU for 1 km impactors is due to the fast removal of such small objects from these regions.

velocities favouring softer impacts. Self-gravity of planetesimals may also restore periastron alignment, as recently showed by Kokubo (personal communication). The scenario that comes out in our simulations can thus be summarized as follows: small to medium size planetesimals are strongly affected by gas drag and their relative velocities are kept low by the periastron alignment. When the gas drag weakens, additional dynamical mechanisms, such as dynamical friction and self–gravity, are still active and help large planetesimals to continue their growth. In the case of massive protoplanetary discs gas drag may be able to do the whole job, allowing the growth of planetesimals until they are big enough to sustain high velocity impacts.

It should also be noted that the high gas densities required to maintain the periastron alignment up to large-size planetesimals might not be unrealistic in the case of the γ Cephei system. It is reasonable to expect that accretion discs surrounding F2 stars, which are progenitors of K III giant stars like γ Cephei are massive compared to the minimum mass solar nebula. Even the density value for the gas adopted by Bodenheimer et al. (2000) for the disc surrounding 47 UMa, a G0V star, may be a lower limit for discs around F2 stars.

An additional conundrum for planetary formation in γ Cephei is whether planetesimals could form in the outer regions of the disc perturbed by the gravity of a secondary star. How sensitive is the dust sticking mechanism to the gravitational pull of the star? It seems reasonable to assume that the sticking mechanism was more efficient in the inner disc, where the perturbations of the secondary star were weaker. The truncation of the planetesimal disc beyond a few AU from the star might thus be supported by the physics of planetesimal formation. At which radial distance did the truncation in the planetesimal population become significant? Only detailed models of planetesimal formation that include the gravitational effects of the companion star can answer this question.

On the other hand, we should not forget that for too high gas densities, small bodies would spiral towards the star on a

short timescale. The question is then: did accretion proceed fast enough to prevent such a loss of small bodies where a large fraction of the mass lies? Planetesimal accretion in the γ Cephei system thus requires a delicate balance between perihelia alignment at large sizes, fast spiralling for small bodies, and proper values of the impact probability.

A numerical model that includes all these effects at once is, at present, beyond computer capabilities. The main result of this section is that gaseous friction opens a window for starting planetesimal accretion within 2.5 AU from the star.

3. Core formation by accretion of protoplanets

In this section, we shall assume that planetesimal accretion could take place and lead to the formation of planetary embryos. This embryo formation could have followed the scenario described by Kortenkamp et al. (2001). These authors have modeled planetesimal accretion in systems with a massive external perturber showing that the combination of gas drag, collisions, and secular perturbations of a massive external body favours orderly growth in the initial phases of planetary accretion followed by a phase of "type II" runaway growth.

We here investigate whether giant impacts between such massive embryos in γ Cephei can lead to the formation of a planetary core whose orbit resembles that of the observed planet and whose mass is at least 10 $M_\oplus$, the mass required to trigger the final phase where the core accretes the remaining gas through rapid infall and forms a giant planet (Pollack et al. 1996). We also evaluate how the timescale of the core formation depends on the initial mass of the embryos, on their number, and on their spatial distribution.

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 between 1 and 2.5 AU where, according to the previous computations, planetesimal accretion is mostly efficient. The orbital evolution of the embryos and their collisions are computed with Chambers' Mercury code (Chambers et al. 2002) which we modified to account for the large perturbations of the binary companion. The number and initial masses of the embryos are derived assuming a reference surface density of solid material at 2.1 AU ranging from 50 to 100 g cm^{-2}. As in the previous section, these values are derived from the Bodenheimer et al. (2000) estimates for the formation of the planetary companion of 47 UMa. The initial masses of the embryos range from a few Lunar mass to the mass of Mars, depending on the adopted value of the disc density. In all the simulations we assume that only a fraction of the mass of the solids in the disc 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 three different distributions of the protoplanets as a function of the distance from the star. This is motivated by the uncertainty about the details of the planetesimal accretion process. Runaway growth, type II runaway growth, orderly growth, or even oligarchic growth can occur depending on the delicate balance between the mass and the velocity distribution. Kortenkamp et al. (2001) have shown that, for a particular binary system, type II runaway growth is to be preferred. However, the type of growth strongly depends on the binary orbital and physical properties, and on the disc parameters like the density and mass distribution. We prefer to cover a large spectrum of possibilities by assuming in our simulations different but equally possible initial conditions for the protoplanets:

1) A population of embryos whose number and location is computed according to a superficial density σ constant on average between 1 and 2.5 AU. 2) A σ that decreases as $1/r$ giving a constant mass for the embryos populating annular portions of the disc surrounding the star. 3) A fixed initial radial distance between the planetary embryos expressed in Hill's radii. In some of the simulations we even include a "proto-core", an embryo with an Earth mass located at 2.1 AU. Initially, all embryos have eccentricities lower than 0.04 and inclinations lower than 1° with respect to the orbital plane of the binary system.

Our simulations with an initial total embryo mass of 25 $M_\oplus$, about 50% of the solid mass in a disc with σ = 50 g cm^{-2}, fail to create a core of 10 $M_\oplus$ within 10 Myr, the typical lifetime of a gaseous disc. The maximum mass of the core achieved in these simulations is 6 $M_\oplus$, which might not be enough to trigger the final gas accretion phase. 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 $M_\oplus$, compatible with $\sigma \simeq 100$ g cm^{-2}, lead to the formation of a core with a mass up to 20 $M_\oplus$ within 10 Myr. However, our simulations all show that the core always ends up within 1.5 AU from the primary star, while the observed planet is at about 2.1 AU. Even when including in the initial protoplanet population a bigger "proto-core" of 1 Earth mass at 2.1 AU, the final accreted core always ends up between 1 and 1.5 AU. Two distinct mechanisms might account for this outcome: 1) in some cases a core might begin to form in the outer regions but migrate inwards due to planetesimal scattering reinforced by the gravitational forces exerted by the binary star which excites the embryos' eccentricities (Fig. 10). 2) In some other cases a core begins to form at around 1 AU. It grows at a faster rate because of the shorter Keplerian orbital period of bodies in inner orbits. This core is able to accrete large protoplanets in outer orbits, since the orbital eccentricity is large due to the companion's perturbations, and the final result is a core around 1.5 AU and almost no remaining material beyond this position. This result holds even when a large "proto-core" is initially placed in the outer disc (Fig. 11). These two mechanisms are a peculiarity of protoplanetary accretion in binary star systems, where large eccentricities among the embryos are excited by the gravitational pull of the secondary star. In a few simulations the "proto-core" is ejected out of the system before it reaches 10 $M_\oplus$, since it is close to the border of the stability region.

In Fig. 12 we show the outcome of a simulation with an intermediate value for the total embryo mass (75 $M_\oplus$) 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 $M_\oplus$. The final giant planet is then expected to orbit closer to the primary star than the observed planet in γ Cephei.

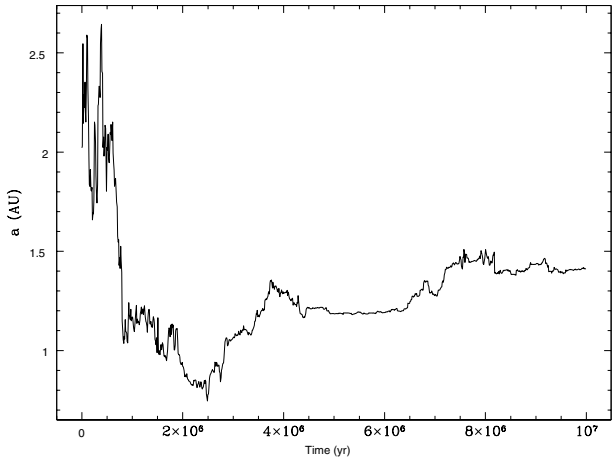

Fig. 10. Migration of the growing core due to scattering of protoplanets. The initial disc extends from 1.5 to 2.5 AU and has a total mass of 75 $M_\oplus$.

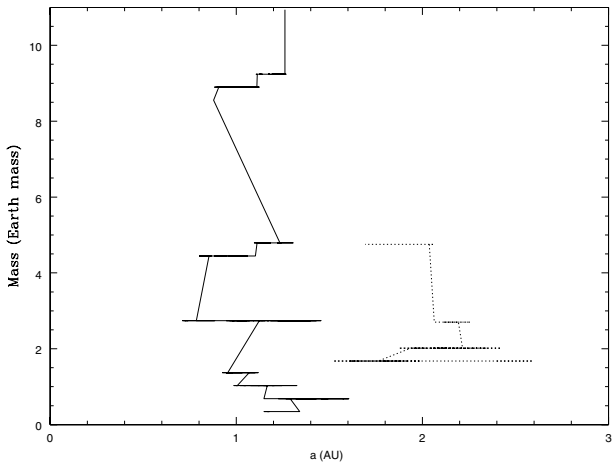

Fig. 11. Evolution, in the (M, a) plane, of a 1 $M_\oplus$ proto-core initially put in the outer disc and of the largest embryo growing in the inner region. The rapid growth of the inner embryo results in the capture of the outer proto-core (see text for details).

4. Discussion and conclusions

The previous results show that planetesimal accretion in γ Cephei depends on a delicate balancing between gas drag and secular perturbations by the secondary star. If this balancing is met, then type II runaway growth (Kortenkamp et al. 2001) might possibly lead to the formation of massive planetary embryos within 2.5 AU from the central star. In the subsequent phase when giant impacts between the embryos build up a massive core, the major problem is not the timescale but the final location of the planet, which is always well inside the actual position of the observed planet. Several explanations might be proposed to account for this discrepancy. A first hypothesis involves the evolution of the whole system. It is possible that the distance between the two stars was larger when the planet formed and that after the planet formation additional mechanisms pushed the secondary star on into a closer orbit. This could be the case if the γ Cephei system was born in a clustered

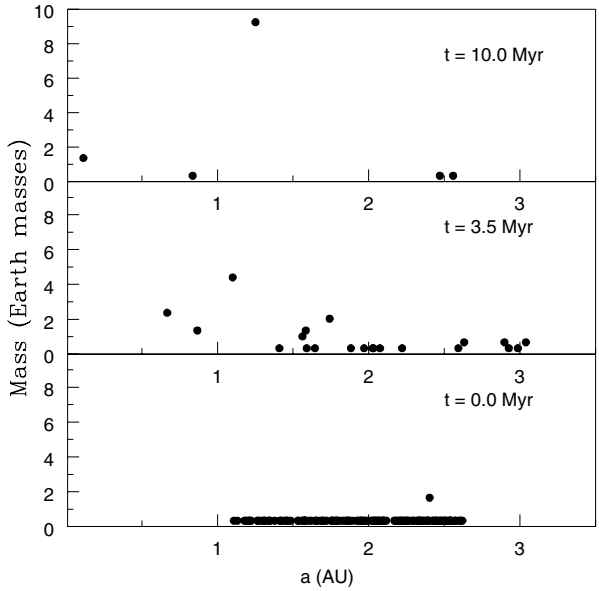

Fig. 12. Snapshots of protoplanet accretion in the γ Cephei system. The initial mass in the embryos is 75 $M_\oplus$ and the superficial density σ decreases with the radial distance as $1/r$.

environment, where close encounters with other young stars may cause perturbations of the binary orbit that tend to shrink it (Heggie 1985). 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 (Reipurth 2000). A more complex mechanism is related to the formation of more than one giant planet around γ Cephei. If the circumstellar disc around the main star was significantly more massive, with a superficial density of solids higher than 100 $\mathrm{g\,cm^{-2}}$, 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 (Marzari et al. 2004). Another and more radical solution would be to renounce the core-accretion model in favour of the alternative disc instability scenario (Boss 2001), but this scenario remains to be quantitatively tested for the γ Cephei system.

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