

# Planet formation in the habitable zone of $\alpha$ Centauri B

P. Thébault,<sup>1,2★</sup> F. Marzari<sup>3</sup> and H. Scholl<sup>4</sup>

<sup>1</sup>*Stockholm Observatory, Albanova Universitetcentrum, SE-10691 Stockholm, Sweden*

<sup>2</sup>*Observatoire de Paris, Section de Meudon, F-92195 Meudon Principal Cedex, France*

<sup>3</sup>*Department of Physics, University of Padova, Via Marzolo 8, 35131 Padova, Italy*

<sup>4</sup>*Laboratoire Cassiopée, Université de Nice Sophia Antipolis, CNRS, Observatoire de la Côte d'Azur, B.P. 4229, F-06304 Nice, France*

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## ABSTRACT

Recent studies have shown that  $\alpha$  Centauri B might be, from an observational point of view, an ideal candidate for the detection of an Earth-like planet in or near its habitable zone (0.5–0.9 au). We study here if such habitable planets can form, by numerically investigating the planet-formation stage which is probably the most sensitive to binarity effects: the mutual accretion of km-sized planetesimals. Using a state-of-the-art algorithm for computing the impact velocities within a test planetesimal population, we find that planetesimal growth is only possible, although marginally, in the innermost part of the habitable zone (HZ) around 0.5 au. Beyond this point, the combination of secular perturbations by the binary companion and gas drag drives the mutual velocities beyond the erosion limit. Impact velocities might later decrease during the gas removal phase, but this probably happens too late for preventing most km-sized objects to be removed by inward drift, thus preventing accretion from starting anew. A more promising hypothesis is that the binary formed in a crowded cluster, where it might have been wider in its initial stages, when planetary formation was ongoing. We explore this scenario and find that a starting separation roughly 15 au wider, or an eccentricity 2.5 times lower than the present ones, is required to have an accretion-friendly environment in the whole HZ.

**Key words:** planets and satellites: formation – stars: individual:  $\alpha$  Centauri – planetary systems: formation.

## 1 INTRODUCTION

The study of planet formation in binary stars is an important issue, as approximately  $\sim 20$  per cent of all detected exoplanets inhabit such systems (Desidera & Barbieri 2007). Even if most of these binaries are very wide, at least three planets have been found in binaries of separation  $\sim 20$  au, the most interesting of them being the  $M \geq 1.6M_{\text{Jup}}$  planet at 2.1 au from the primary of the  $\gamma$  Cephei system, which has been the subject of several planet-formation studies (Thébault et al. 2004; Jang-Condell, Mugaauer & Schmidt 2008; Kley & Nelson 2008).

However, the system which has been most thoroughly investigated is one where no planet has been detected so far:  $\alpha$  Centauri.<sup>1</sup> Holman & Wiegert (1997) have shown that, for the coplanar case, the  $< 3$  au region around  $\alpha$  Cen A can harbour planets on stable orbits, while Barbieri, Marzari & Scholl (2002) and Quintana et al. (2002, 2007) have found that the final stages of planetary formation,

the ones leading from large planetary embryos to the final planets, are possible in the inner  $< 2.5$  au region. However, Thébault, Marzari & Scholl (2008, hereafter TMS08) showed that the earlier stage leading, through runaway growth in a dynamically quiet environment (e.g. Lissauer 1993), from km-sized planetesimals to the embryos is much more affected by the companion star's perturbations. Indeed, the coupled effect of these secular perturbations and drag due to the gas in the nebulae leads to a strong orbital phasing according to planetesimal sizes. This differential phasing induces high collision velocities for any impacts between objects of sizes  $s_1 \neq s_2$ , which can strongly slow down or even halt the accretion process. As a result, the region beyond 0.5 au (0.75 au for the most extreme cases explored) from the primary is hostile to mutual accretion of planetesimals, and thus to the in situ formation of planets. The *presence* of planets in these regions, however, cannot be ruled out, in the light of possible additional mechanisms not taken into account in the simulations, such as a change of the dynamical environment once gas has been dispersed, or outward migration of planets formed closer to the star, or a change in the binary's separation during its early history.

We reinvestigate here these issues for the case of the secondary star  $\alpha$  Centauri B. Indeed, a recent study by Guedes et al. (2008)

★E-mail: philippe.thebault@obspm.fr

<sup>1</sup> Endl et al. (2001) rule out the presence of a  $M \geq 2.5M_{\text{Jupiter}}$  planet at any radial distance.

has shown that, in addition to the final embryos-to-planets stage being possible within  $\sim 2.5$  au from it, this star would be an almost perfect candidate for the detection of a potential terrestrial planet by the radial velocity method. This is mainly not only because of its great proximity, but also because it is exceptionally quiet. Moreover, because of its lower luminosity, its habitable zone (HZ) lies much closer, 0.5 to 0.9 au (Guedes et al. 2008), than that of  $\alpha$  Cen A ( $\sim 1$  to 1.3 au; e.g. Barbieri et al. 2002).

In this Letter, we first numerically study the dynamics of the planetesimal accretion phase in a similar way as for  $\alpha$  Cen A, by estimating the extent of the accretion-friendly region around the central star (Section 2). We then push our studies a step further than in TMS08 by quantitatively exploring two mechanisms which could potentially increase the odds for planet formation in the HZ (Section 3). Conclusions and perspectives are given in the last section.

## 2 SIMULATIONS

### 2.1 Model and setup

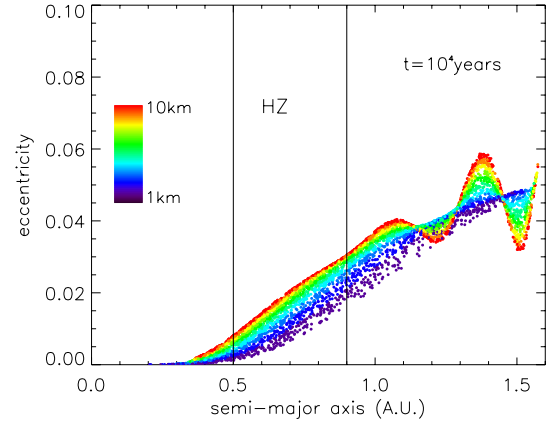
We consider a disc of  $10^4$  test planetesimals extending from 0.3 to 1.6 au from the central star, starting on quasi-circular orbits such as initial encounter velocities  $\langle \Delta v \rangle < 1 \text{ m s}^{-1}$ , and with a physical radius  $s$  in the  $1 < s < 10 \text{ km}$  range. The binary's parameters are taken from Poubais et al. (2002): semimajor axis  $a_b = 23.4 \text{ au}$ , eccentricity  $e_b = 0.52$ ,  $M_A = 1.1 M_\odot$  and  $M_B = 0.93 M_\odot$ . We follow the dynamical evolution of the planetesimal population for  $t = 10^4 \text{ yr}$ , the typical time-scale for runaway growth, under the coupled influence of the companion star's (here  $\alpha$  Cen A) perturbations and gas drag, using the deterministic code developed by Thébault & Brahic (1998). All test planetesimal collisions are tracked with the code's build-in close-encounter search routine, looking at each time-step for all intersecting particle trajectories with the help of the classical 'inflated radius' procedure (see section 2.1 of TMS08 for more details). The gas disc is assumed axisymmetric with a volumic density profile following  $\rho_g = \rho_{g0} r_{\text{au}}^q$ , where we consider as a nominal case the Minimum Mass Solar Nebula (MMSN), with  $q = -2.75$  and  $\rho_{g0} = 1.4 \times 10^{-9} \text{ g cm}^{-3}$  (Hayashi 1981), exploring  $\rho_{g0}$  and  $q$  as free parameters in separate runs.

All mutual encounters and corresponding encounter velocities are tracked and recorded in order to derive  $\langle \Delta v \rangle_{s_1, s_2}$  matrices for all possible impactor pairs of sizes  $s_1$  and  $s_2$ . These velocity values are then interpreted in terms of accreting or eroding encounters by comparing them, for each impacting pair, to two threshold velocities (for more details, see Thébault, Marzari & Scholl 2006 and TMS08):

(i)  $v_{\text{esc}(s_1, s_2)}$ : the escape velocity of the impacting pair. This velocity gives approximately the limit below which single-star-like runaway accretion is possible (when accretion rates are enhanced by the gravitational focusing factor).

(ii)  $v^*_{(s_1, s_2)}$ : the velocity above which impacts preferentially lead to mass loss rather than mass accretion. This value is obtained from estimates of the critical threshold energy for catastrophic fragmentation  $Q^*_{(s_1, s_2)}$ . Given the large uncertainties regarding the possible values for  $Q^*_{(s_1, s_2)}$ , we consider two limiting values,  $v^*_{(s_1, s_2)\text{low}}$  and  $v^*_{(s_1, s_2)\text{high}}$ , corresponding to a weak and hard material assumption, respectively.

Finally, at any given location in the system, the global balance between accreting and eroding impacts is estimated assuming a size distribution for the planetesimal population, weighting the contribution of each  $(s_1, s_2)$  impact by its normalized probability according



**Figure 1.** Eccentricity versus semimajor axis graph at the end ( $10^4 \text{ yr}$ ) of the nominal case run. The colour scale shows the different particle sizes. The two vertical lines indicate the estimated location of the HZ.

to the assumed size distribution. As a nominal case, we assume a Maxwellian peaking at the median value  $s_{\text{med}} = 5 \text{ km}$ , but other distributions (Gaussians, power laws) are also explored.

### 2.2 Results: nominal case

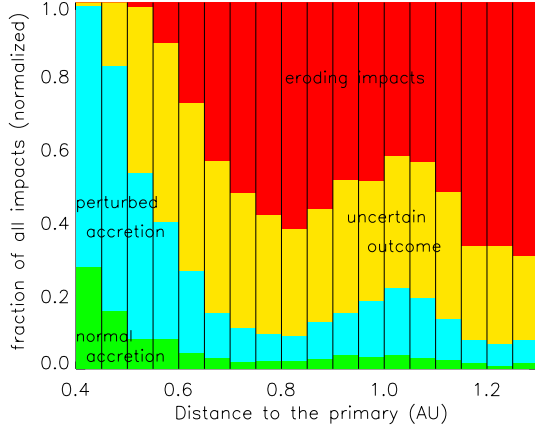
The (e,a) graph displayed in Fig. 1 clearly illustrates the effect of differential orbital phasing as a function of sizes. Smaller planetesimals align to orbits with lower eccentricities than that of the bigger objects.<sup>2</sup> Note that in the outer regions (beyond  $\sim 1 \text{ au}$ ), residual eccentricity oscillations are observed for the larger bodies. This is because these objects, which are less affected by gaseous friction, have not had the time yet to fully reach the equilibrium orbit forced by gas drag.

Fig. 2 shows how  $\langle \Delta v \rangle_{s_1, s_2}$  resulting from this differential phasing can be interpreted in terms of accreting versus eroding impacts. This graph displays the relative weights of the possible types of collision outcomes as a function of distance to  $\alpha$  Cen B, for our nominal case (MMSN gas disc), assuming that the planetesimal size distribution follows a Maxwellian centred on 5 km. By comparing this graph to the equivalent graph for  $\alpha$  Cen A (fig. 3 of TMS08), we see that results are roughly comparable for both stars. Schematically, the region beyond  $\sim 0.5 \text{ au}$  from the primary is hostile to planetary accretion. This similarity of the results is mostly due to the fact that the mass ratio between the two stars is close to 1 ( $\sim 0.85$ ), and that the strongest perturbations of  $\alpha$  Cen A on  $\alpha$  Cen B are partly compensated by the lower Keplerian velocities around that smaller star. One important difference, however, is that the HZ around  $\alpha$  Cen B lies closer to the star: 0.5 to 0.9 au (Guedes et al. 2008). This means that its innermost part lies at the outer-edge of the accretion-friendly region, thus opening a possibility, although marginal, for planet formation there.

### 2.3 Parameter exploration

To check the robustness of these results with respect to our choice of parameters for the nominal case, we first explore other possible gas-disc profiles by varying both the slope  $q$  and the density  $\rho_{g0}$  at 1 au. We find that the only case which leads to a wider accretion-friendly zone is that of a dense  $10 \times \text{MMSN}$  gas disc, for which

<sup>2</sup> This differential alignment in  $e$  is strengthened by the associated differential alignment of the pericentre angle (e.g. Thébault et al. 2006).



**Figure 2.** Relative importance of different types of collision outcomes, as a function of distance to the primary star ( $\alpha$  Cen B), at  $t = 10^4$  yr for our nominal case. Each  $\Delta v_{(s_1, s_2)}$  for an impact between bodies of sizes  $s_1$  and  $s_2$  is interpreted in terms of eroding impacts [if  $\Delta v > v_{(s_1, s_2)\text{high}}$ ], accreting impacts despite increased velocities [‘perturbed accretion’ for  $v_{\text{esc}(s_1, s_2)} < \Delta v < v_{(s_1, s_2)\text{low}}$ ] or unperturbed ‘normal’ accretion [ $\Delta v < v_{\text{esc}(s_1, s_2)}$ ]. For  $v_{(s_1, s_2)\text{low}} < \Delta v < v_{(s_1, s_2)\text{high}}$ , we do not draw any conclusions. The contribution of each impact is then weighted assuming that the size distribution for the planetesimals follows a Maxwellian centred on 5 km (see text for details).

**Table 1.** Outer limit  $r_{\text{acc(out)}}$  of the accretion-friendly inner zone, as defined by the region where the ‘green’ and ‘blue’ areas make up more than 50 per cent of the collision outcomes (see Fig. 2), for test runs exploring different free parameters: gas density  $\rho_{g0}$  at 1 au, slope  $q$  of the  $\rho_g \propto r^q$  gas density profile and assumed size distribution for the planetesimal population.

Set-up	$r_{\text{acc(out)}}$
Nominal case	0.5 au
$\rho_{g0} = 1.4 \times 10^{-10} \text{ g cm}^{-3}$ (0.1×MMSN)	0.3 au
$\rho_{g0} = 1.4 \times 10^{-8} \text{ g cm}^{-3}$ (10×MMSN)	0.8 au
$\rho_g \propto r^{-2.25}$ ( $\alpha$ viscous disc)	0.45 au
$\rho_g \propto r^{-1.75}$	0.4 au
Size dist.: Gaussian, $\sigma^2 = (2 \text{ km})^2$	0.55 au
Size dist.: Gaussian, $\sigma^2 = (1 \text{ km})^2$	0.6 au
Size dist.: Gaussian, $\sigma^2 = (0.5 \text{ km})^2$	1.1 au
Size dist.: power law $dN \propto s^{-3.5} ds$	0.5 au

this region extends up to  $\sim 0.8$  au (Table 1). All other gas-disc cases lead to equally narrow or even narrower accretion-friendly regions than for our nominal case, except for a purely academic gas-free case. Of course, our axisymmetric gas-disc assumption is probably a crude simplification of the real behaviour of a gas disc perturbed by a companion star. However, preliminary hydro+ $N$ -body runs performed by Paardekooper, Thébault & Mellema (2008) show that the build up of an eccentricity for the gas disc, although this mechanism is yet not fully understood, always leads to *higher* perturbations and impact velocities in the planetesimal population. As a consequence, our axisymmetric disc case might be regarded as a best-case scenario and our results to be on the conservative side (for a more detailed discussion and justification for our choice of an axisymmetric disc, see TMS08).

Another crucial parameter which has been explored is the assumed size distribution for the planetesimal population, as it is a parameter poorly constrained from planet-formation models (see discussion in Thébault et al. 2006). For any ‘reasonable’ distri-

butions, we do not observe a significant displacement of the accretion/erosion radial limit. Only a very peaked, almost Dirac-like Gaussian of variance  $\sigma^2 = (0.5 \text{ km})^2$  leads to mostly accreting impacts in the whole HZ (Table 1).

### 3 DISCUSSION

The results of the previous section show that, as was the case for  $\alpha$  Cen A, the region allowing km-sized planetesimal accretion is much more limited than the one allowing the final stages of planet formation (starting from large embryos): the accretion-friendly zone only extends up to  $\sim 0.5$  au for our nominal case, as compared to the estimated 2.5 au for the embryos-to-planets phase (Guedes et al. 2008, and reference therein).

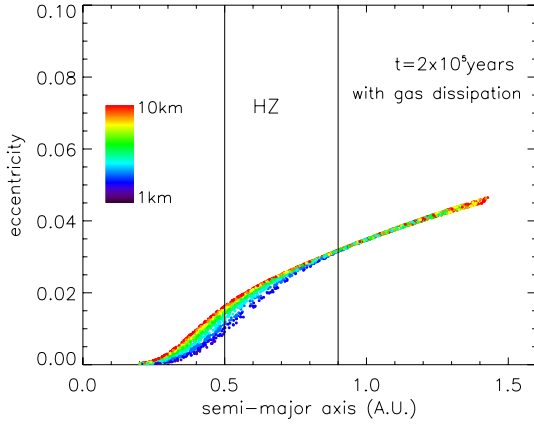
The only cases leading to an accretion-friendly environment in a wider area than for the nominal run are (a) the gas-free case, (b) the very-peaked Gaussian size distribution and (c) the 10×MMSN run. Cases (a) and (b) are obviously very unrealistic test runs, but even case (c) is probably here of limited physical significance. Indeed, assuming such a high-mass disc around a  $0.9 M_\odot$  star appears as a rather extreme hypothesis, which is not backed by theoretical estimates or observational data (e.g. Andrews & Williams 2007). For a binary system, this issue gets even more critical, as the expected outer truncation of the circumprimary gas disc probably depletes it from a substantial amount of its mass reservoir (e.g. Jang-Condell et al. 2008), making the 10×MMSN hypothesis even more questionable, although it cannot be completely ruled out.

Apart from this massive gas-disc case, the  $r_{\text{acc(out)}} \sim 0.5$  au limit allows in principle for planetesimal accretion to occur in the innermost part of the HZ, which is estimated to extend from 0.5 to 0.9 au (as compared to  $\sim 1$  to 1.3 au for  $\alpha$  Cen A). However, even if some planetesimal accretion is possible, it could probably not be what it is in the standard planet-formation scenario. Indeed, even if the  $\sim 0.5$  au region is accretion friendly, relative velocities there have values higher than what they should be in an unperturbed system (i.e., approximately the escape velocities of km-sized bodies; e.g. Lissauer 1993). This means that the gravitational focusing factor, which is the cause of the fast runaway growth mode, is significantly reduced or cancelled. Growth would thus have to be much slower, maybe orderly or of the ‘type II’ runaway identified by Kortenkamp, Wetherill & Inaba (2001). In short, planetesimal accretion is not possible in the HZ, except in the innermost region around 0.5 au where it should be significantly different from what it is around a single star.

However, no conclusions regarding the *presence* of planets in the HZ can be directly drawn from these results, because of the possible effect of additional processes not taken into account in our simulations. In TMS08, we reviewed some of these possible mechanisms, and concluded that while some of them might not significantly affect our conclusions (like bigger ‘initial’ planetesimals or re-accretion in the subsequent gas-free disc), others might indeed open for a possible presence of a planet in the terrestrial region. We reinvestigate here these mechanisms in more details, focusing specifically on the two most promising scenarios, that of orbital re-phasing during an extended gas dispersion phase and of a greater separation for the early binary.

#### 3.1 Re-phasing during gas dispersion

Xie & Zhou (2008) have investigated, for the specific case of the  $\gamma$  Cephei binary, what happens to a planetesimal swarm *during* the gas dispersal period. They have identified an interesting mechanism: if



**Figure 3.** (e,a) graph, after  $t = 2 \times 10^5$  yr, for the run with gas dissipation. Gas dissipation starts at  $t = 10^4$  yr and has a time-scale  $\tau_{\text{diss}} = 10^5$  yr (see text for details).

the gaseous component is slowly removed from the disc, all planetesimal orbits are progressively re-phased towards the same orbits regardless of their sizes. This leads to lower, possibly accretion-friendly, impact velocities. They concluded that this might allow, under certain circumstances, for planetesimal accretion to start anew once this realignment is achieved. We explore this possibility for the present  $\alpha$  Cen B case, assuming the same parameters for gas dispersion as Xie & Zhou (2008):  $\rho_g \propto (t/\tau_{\text{diss}})^{-1.5}$ , with  $\tau_{\text{diss}} = 10^5$  yr. The dissipation is started at  $10^4$  yr, the end of our nominal run, when all orbits have reached their size-dependent alignment in the HZ.

Fig. 3 shows the dynamical state of the system after  $2\tau_{\text{diss}} = 2 \times 10^5$  yr and clearly illustrates the efficient re-phasing of all orbits, which is almost complete in the  $>0.8$  au region. In this outer region,  $\langle \Delta v \rangle$  are low enough to allow accretion of all remaining objects. However, this encouraging result is undermined by several problems. The first one is that, in this accretion-friendly outer region, no object smaller than  $\sim 4$  km is left after  $2\tau_{\text{diss}}$ , because the time it takes for most of the gas to be dispersed is long enough (a few  $10^5$  yr) to have a significant inward drift of all smaller bodies.<sup>3</sup> In most of the HZ, however, small planetesimals are still present, but here full orbital re-phasing is not achieved yet, so that the dynamical environment, even if the situation is slightly improved with respect to the nominal run, is still globally hostile to accretion. Only after  $\sim 5\tau_{\text{diss}} = 5 \times 10^5$  yr do  $\langle \Delta v \rangle$  become low enough to allow accretion in the whole HZ, by which time all small objects have here also been removed.

The second problem is that, even for the larger  $\geq 4$  km planetesimals, the favourable conditions shown in Fig. 3 are only reached after an accretion-hostile transition period of a few  $\tau_{\text{diss}}$ . The question is then how these objects might survive this long period during which most impacts will erode them. These erosion processes cannot be followed with the  $N$ -body models used here, but it is likely that most large planetesimals will be fragmented into smaller debris which will be quickly removed from the system by fast inward drift.

For all these reasons, we do not believe that gas dispersal opens the possibility for planetesimal accretion to start anew after a few  $\tau_{\text{diss}}$ . However, the re-phasing mechanism during gas dispersal iden-

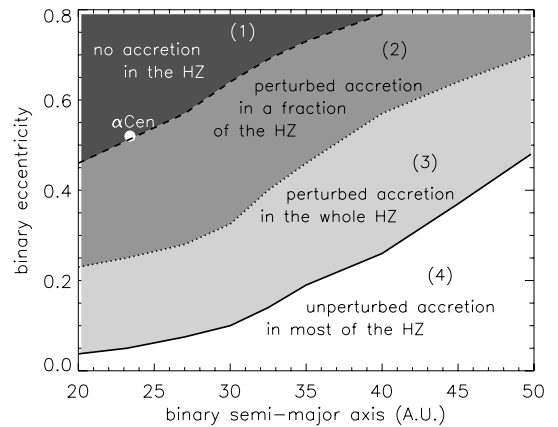
tified by Xie & Zhou (2008) is definitely worth studying in more details. One crucial, and yet almost unexplored, issue is, for instance, the relative timing between the planetesimal accretion phase (in particular its start) and the parallel viscous evolution of the gas disc. Indeed, as pointed out by Xie & Zhou (2008), the steady evolution of the gas-disc profile, due to viscous angular momentum redistribution and accretion, can lead to a gas density decrease of several orders of magnitudes long before its ‘definitive’ and abrupt dispersion, at 5 to 10 Myr, resulting from photoevaporation-induced disc truncation (see e.g. fig. 1 of Alexander, Clarke & Pringle 2006). The question is where (or when) to place the planetesimal accretion phase in this picture.

### 3.2 Wider initial binary separation

Most stars are born in clusters. As such, they spend their early life in an environment where the risk for close stellar encounters is relatively high. For a binary system, such encounters could have dramatic effects, breaking it up or significantly modifying its initial orbit. Conversely, a present-day binary could be what is left of an initially triple (or more) system (Marzari & Barbieri 2007a,b). As a consequence, there might be an important difference between the present-day orbit of a binary system and the one it had when planetary-formation processes were at play.

In order to have an idea of the statistical chances for an  $\alpha$  Centauri-like binary to have an initially different orbit, we take as a reference the work of Malmberg, Davies & Chambers (2007), who studied the dynamical evolution of a typical open cluster. They found that most binaries of initial separation  $\leq 200$  au are not broken up during the cluster’s lifetime. However, a fraction of these ‘hard’ binaries suffer stellar encounters which alter their orbits. The net result of these encounters is to shrink the binaries’ orbits, so that separations of young binaries tend to be larger, with an environment which is thus more favourable to planet formation. Fig. 4 of Malmberg et al. (2007) indicates that  $\sim 50$  per cent of binaries with separation  $\sim 20$  au have suffered an orbit-modifying encounter. There is thus roughly one chance in two that  $\alpha$  Centauri had a wider separation during the early stages of planet formation if it formed in a dense cluster.

The crucial question here is which initial orbital configurations could have allowed planetesimal accretion to occur in the HZ of  $\alpha$  Cen B. We investigate this issue by running a series of 31 test runs for  $20 < a_b < 50$  au and  $0 < e_b < 0.8$  (Fig. 4). Not surprisingly, we



**Figure 4.** Dominant collision outcome (erosion, perturbed accretion, unperturbed accretion; see Fig. 2) in the HZ (0.5–0.9 au) around  $\alpha$  Centauri B, for different configurations of the binary’s orbit.

<sup>3</sup> This issue had already been identified by Xie & Zhou (2008) but did not show up in their simulations because of the numerically imposed re-injection at the outer boundary of all objects lost at the inner one.

see that present-day  $\alpha$  Cen B lies almost at the limit where accretion, although highly perturbed, becomes possible in the innermost part of the HZ. For the same  $e_b = 0.52$  as today, perturbed accretion in part of the HZ is possible for  $23 \leq a_b \leq 37$  au. In order to have the HZ become fully accretion friendly, one needs  $a_b \geq 37$  au, while *unperturbed* single-star-like accretion requires  $a_b \geq 52$  au, more than twice the present-day separation. The situation gets, of course, more favourable if one assumes a lower initial  $e_b$  for the binary. As an example, with  $e_b = 0.26$  (half of the present-day value), the whole HZ becomes accretion friendly for  $a_b \geq 26$  au and allows unperturbed accretion for  $a_b \geq 40$  au.

These results are of course only a first step towards understanding this complex issue. A crucial point is to quantitatively estimate what the probability for a given  $\Delta a_b$  and  $\Delta e_b$  ‘jump’ is. As an example, how likely is it for a present-day  $\alpha$  Centauri-like system to have originated from the accretion-friendly regions (3) or (4) in Fig. 4? The answer to these questions requires very detailed and encompassing numerical explorations, which have, to our knowledge, not been performed yet. Marzari & Barbieri (2007a,b) have studied in great detail the dynamical outcomes of individual encounters, but decoupled from the general cluster context, while the cluster evolution study of Malmberg et al. (2007) does not give statistical information about the amplitudes of binary orbital changes.

#### 4 CONCLUSIONS AND PERSPECTIVES

We have numerically investigated planetesimal accretion around  $\alpha$  Centauri B. Our main conclusions can be summarized as follows.

(i) Planetesimal accretion is marginally possible in the innermost parts,  $\sim 0.5$  au, of the estimated HZ. Beyond this point, high collision velocities, induced by the coupling between gas friction and secular perturbations, lead to destructive impacts. Moreover, even in the  $\sim 0.5$  au region,  $\langle \Delta v \rangle$  are increased compared to an unperturbed case. Thus, ‘classical’, single-star-like runaway accretion seems to be ruled out.

(ii) These results are relatively robust with respect to the planetesimal size distribution or gas-disc profile, except for a very massive, and probably unrealistic,  $10 \times \text{MMSN}$  gas disc.

(iii) We confirm the conclusions of several previous studies that the planetesimal-to-embryo stage is much more affected by binarity effects than the subsequent embryos-to-final-planets stage.

(iv) As in Xie & Zhou (2008), we find that later progressive gas dispersal reduces all  $\langle \Delta v \rangle$  to values that might allow accreting impacts. However, we find that the system has first to undergo a long accretion-hostile transition period during which most of the smaller planetesimals are removed by inward drift and most bigger objects are probably fragmented into small debris. Thus, the positive effect on planetesimal accretion is probably limited.

(v) We quantitatively investigate to what extent a wider initial binary separation, later reduced by stellar encounters in an early cluster environment, could have favoured planetesimal accretion. We find that, for a constant  $e_b$ , an entirely accretion-friendly HZ requires an initial  $a_b \geq 37$  au, while normal unperturbed accretion

is only possible for  $a_b \geq 52$  au. The statistical likelihood of such orbital changes in early open clusters remains to be quantitatively estimated.

We conclude that although the presence of planets further out cannot be fully excluded, the most likely place to look for a habitable terrestrial planet would be around 0.5 au. According to Guedes et al. (2008), the detection of such a planet could be possible, if its mass is  $\geq 1.8 M_\oplus$ , after 3 yr of high cadence observations, provided that the noise spectrum is white. Let us, however, point out again that the  $\sim 0.5$  au region around  $\alpha$  Cen B is dynamically perturbed by the binary, so that the formation of a planet there cannot have followed the standard single-star scenario (unless the initial binary separation was much larger; see Section 3.2). The planet-formation process in such a perturbed environment, which could concern many binary systems of intermediate ( $\sim 20$  au) separations, is an important issue which remains to be investigated. Another crucial issue which remains to be investigated is what happens *before* the phase studied here. Indeed, our study implicitly assumes that km-sized planetesimals could form from smaller grains and pebbles, but the validity of this assumption has to be critically examined.

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