

# Asteroid flux towards circumprimary habitable zones in binary star systems: I. Statistical overview

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## ABSTRACT

**Context.** So far, multiple stellar systems harbor more than 130 extra solar planets. Dynamical simulations show that the outcome of planetary formation process can lead to various planetary architecture (i.e. location, size, mass and water content) when the star system is single or double.

**Aims.** In the late phase of planetary formation, when embryo-sized objects dominate the inner region of the system, asteroids are also present and can provide additional material for objects inside the habitable zone (hereafter HZ). In this study, we make a comparison of several binary star systems and their efficiency to move icy asteroids from beyond the snow-line into orbits crossing the HZ.

**Methods.** We modeled a belt of 10000 asteroids (remnants from the late phase of planetary formation process) beyond the snow-line. The planetesimals are placed randomly around the primary star and move under the gravitational influence of the two stars and a gas giant. As the planetesimals do not interact with each other, we divided the belt into 100 subrings which were separately integrated. In this statistical study, several double star configurations with a G-type star as primary are investigated.

**Results.** Our results show that small bodies also participate in bearing a non-negligible amount of water to the HZ. The proximity of a companion moving on an eccentric orbit increases the flux of asteroids to the HZ, which could result into a more efficient water transport on a short timescale, causing a heavy bombardment. In contrast to asteroids moving under the gravitational perturbations of one G-type star and a gas giant, we show that the presence of a companion star can not only favor a faster depletion of our disk of planetesimals but can also bring 4 – 5 times more water into the whole HZ.

**Key words.** Celestial mechanics – Methods: statistical – Minor planets, asteroids: general – binaries: general

## 1. Introduction

Nearly 130 extra solar planets in double and multiple star systems have been discovered to date. Roughly one quarter of these planets is orbiting close to or even crossing their system's habitable zone (HZ), i.e. the region where an Earth-analog could retain liquid water on its surface [Rein, 2014]. While most of these planets are gas giants, the incredible ratio of one in four planets to be at least partly in the HZ seems to make binary star systems promising targets in the search of a second Earth, especially for the next generation of photometry missions CHEOPS, TESS and PLATO-2.0. About 80 percent [Rein, 2014] of the currently known planets in double star systems are in so-called S-type configurations [Dvorak, 1984], i.e. the two stars are so far apart so that the planet orbits only one stellar component without being destabilized. As most of the wide binary systems host not only one gas giant, their dynamical evolution is quite complex. The question whether habitable worlds can actually exist in such environments is, therefore, not a trivial one. Previous works on early stages of planetary formation show that planetesimals accretion can be more difficult than in single star systems [Thebault and Haghighipour, 2014, and references therein]. This in turn can question the possibility of forming embryos in such systems. However, studies of late stages of planetary formation show that, should embryos manage to form

despite these adverse conditions, then the dynamical influence of companion stars is not prohibitive to form Earth-like planets [Raymond et al., 2004, Haghighipour and Raymond, 2007]. Furthermore, it was shown that binary star systems in the vicinity of the Solar System are capable of sustaining habitable worlds, once they are formed [Eggel et al., 2013, Jaime et al., 2014]. As the amount of water on a planet's surface seems to be crucial to sustain a temperate environment [Kasting et al., 1993], it is important to identify possible sources. For Earth, two mechanisms seem to be important: i) endogenous outgassing of primitive material and ii) exogenous impact by asteroids and comets sources have been established. Since neither can explain the amount and isotope composition of Earth's oceans in itself, however, models that favor a combination of both sources seem to be more successful [Izidoro et al.]. The amount of primordial water that is collected during formation phases of planets in S-type orbits in binary star systems containing additional gas giants has been studied by Haghighipour and Raymond [2007]. They have shown that the planets formed in a circumstellar HZ may have collected between 4 and 40 Earth oceans from planetary embryos, but main trend to appear was: the more eccentric is the orbit of the binary, the more eccentricity is also injected into the gas giant's orbit. This in turn leads to fewer and dryer terrestrial planets. Quintana et al. [2007] emphasize that during the late stages of planetary formation, without the

**Table 1.** Physical properties of the secondary star in the binary system.

Stellar-type	$M_{\star}$ [ $M_{\odot}$ ]	$L_{\star}$ [ $L_{\odot}$ ]	$T_{\star}$ [K]
G	1.0	1.0	5780
K	0.7	0.38	5200
M	0.4	0.08	3800

presence of gas giant planets, binary stars with periastron  $> 10$  au have a minimal effect on terrestrial planet formation within  $\sim 2$  au of the primary, whereas binary stars with periastron  $\leq 5$  au restrict terrestrial planet formation to within  $\sim 1$  au of the primary star. Quintana and Lissauer [2006] studied the late stages of planetary formation in P-type orbits in binary star systems (with maximum separation equal to 0.4 au and maximum secondary’s eccentricity equal to 0.8) including Jupiter and Saturn-like planets. They conclude that the higher the secondary’s apoapsis, the smaller the number of planets formed and the lower their mass. The anti-correlation between a system’s eccentricity and the number of planets has also been found in a preliminary interpretation of observation statistics by Limbach and Turner [2014]. These results indicate that the likelihood of finding habitable planets in such an environment could be small.

Stochastic simulations proved that planet can also be formed almost dry in the circumprimary HZ of binary star systems [Haghighipour and Raymond, 2007]. However, as emphasized by these authors, water delivery in the inner solar system is not only due to radial mixing of planetary embryos. Smaller objects can also contribute as shown in Raymond et al. [2007]. Indeed, they highlighted that water delivery from smaller planetesimals is statistically robust and should supply terrestrial planets with a significant water source of perhaps three to 10 oceans. In our work, we aim to answer how much water can be transported into the HZ via small bodies, remnants from the late phase of the planetary formation, providing thus other water sources to embryos. We statistically study the dynamics of an asteroid belt in such systems and we treat this problem in a self-consistent manner as all the gravitational interactions in the system as well as water loss of the planetesimals due to outgassing are accounted for. Our main goal is to examine the influence of the secondary star on the flux of small bodies from icy regions to the HZ and the efficiency of the water transport within a short timescale of 10 Myrs.

## 2. Initial conditions and dynamical model

Our study is focused on a primary G-type star with mass equal to one solar mass and we investigate the dynamical effect of a secondary of either G, K or M-type with physical properties expressed in Table 1. The studied binary star systems encompass relatively tight configurations, i.e. semi-major axes in a range of  $a_b \in [25 : 100]$  au. This parameter has been changed in steps of 25 au in our simulations. The secondary is on an elliptical coplanar orbit with eccentricities  $e_b \in [0.1 : 0.5]$  increased in steps of 0.2. In total 12 configurations have been investigated for any given stellar type of the companion. In addition, we consider a gas giant located at  $a_{GG} = 5.2$  au on a circular coplanar orbit, with a mass equal to Jupiter’s mass.

**Table 2.** Mass loss in the simulated collisions. Mass loss is defined as the quantity not in the surviving bodies (one for erosion, two for hit-and-run and merging) after one impact.

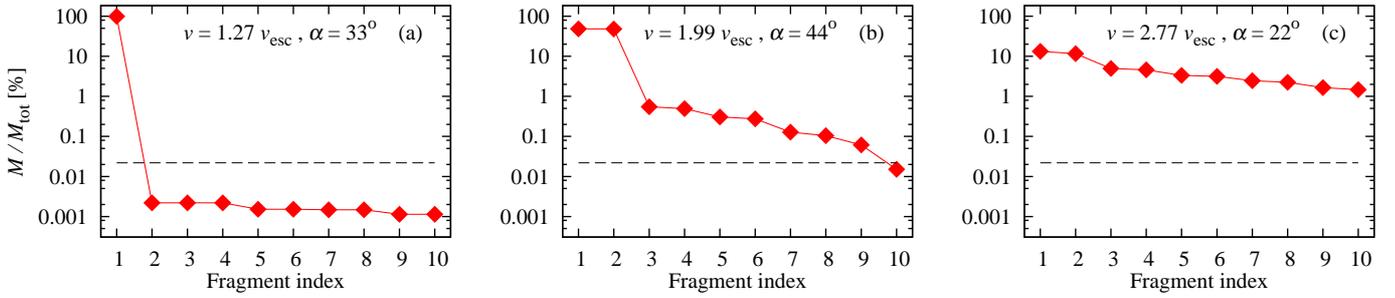
Collision scenario			Mass
$v$	$\alpha$	Type	[wt-%]
[ $v_{esc}$ ]	[ $^{\circ}$ ]		
1.00	20	merging	0.6
1.27	33	merging	0.9
1.37	42	hit & run	0.4
1.99	44	hit & run	3.5
2.77	22	erosion	75.2

A disk of planetesimals is modeled as a ring of 10000 asteroids with masses similar to main belt objects in the Solar System and each asteroid was assigned an initial water mass fraction (hereafter wmf) of 10% [Abe et al., 2000, Morbidelli et al., 2000]. During the late phase of planetary formation, if the inner region of the system is mainly dominated by large embryos (following a specific mass distribution) with masses between Moon to Mars size [Raymond et al., 2004, Haghighipour and Raymond, 2007], debris resulting from collisions of such embryos are also present. To determine the lower and upper limits for the asteroids’ masses, we performed independent preliminary simulations with a 3D smooth particle hydrodynamics (SPH) code [Schäfer, 2005, Maindl et al., 2013]. First-order consistency is achieved by a tensorial correction as discussed in Schäfer et al. [2007]. It includes self-gravity and models material strength using the full elasto-plastic continuum mechanics and the Grady-Kipp fragmentation model for fracture and brittle failure [Grady and Kipp, 1980, Benz and Asphaug, 1994]. The scenarios involve collisions of rocky basaltic objects with one lunar mass at different encounter velocities and angles  $\alpha$ . The latter are defined in a way so that  $\alpha = 0^{\circ}$  corresponds to a head-on collision. The scenarios start with the bodies five diameters apart to let the SPH particle distribution settle. This preliminary simulation time-span was 2000 min. In an earlier study, most collisions of Moon-sized bodies in the Solar System’s HZ were found to happen at velocities  $v \lesssim 2v_{esc}$  at arbitrary collision angles [Maindl and Dvorak, 2014]. We chose initial conditions in this range which are in the merging/partial accretion and hit-and-run domain of the collision outcome map [cf. Agnor and Asphaug, 2004, Leinhardt and Stewart, 2012, Maindl et al., 2014]. Expecting a somewhat higher spread in  $v$  in binary systems we also included a scenario in the erosion/mutual destruction domain. Table 2 lists the collision scenario parameters and gives the resulting mass loss of the survivors (one body for merging, two bodies in the erosion and hit-and-run scenarios, respectively) after one impact.

The fragment sizes beyond the survivors drop significantly in the hit-and-run and merging scenarios (Fig. 1a, b): In the mutual destruction case, all of the ten largest fragments possess masses  $\geq 1\%$  of the total system mass, which is  $\sim$  Ceres’ mass<sup>1</sup>, and hundreds are above the “significant” fragment threshold in the sense of Maindl et al. [2014]. The smallest fragment consists of one SPH particle (0.001% of the total mass for 100k SPH particles) which corresponds to  $\sim 0.1\%$  of Ceres’ mass. As increasing the number of SPH particles will result in even smaller fragments, this mass is an upper limit for the smallest fragment. As this latter will contain  $\sim 0.006\%$  Earth-oceans units<sup>2</sup>, we chose to neglect the water contribution of smaller

<sup>1</sup> Ceres’ mass is equal to  $4.73 \times 10^{-10} M_{\odot}$ .

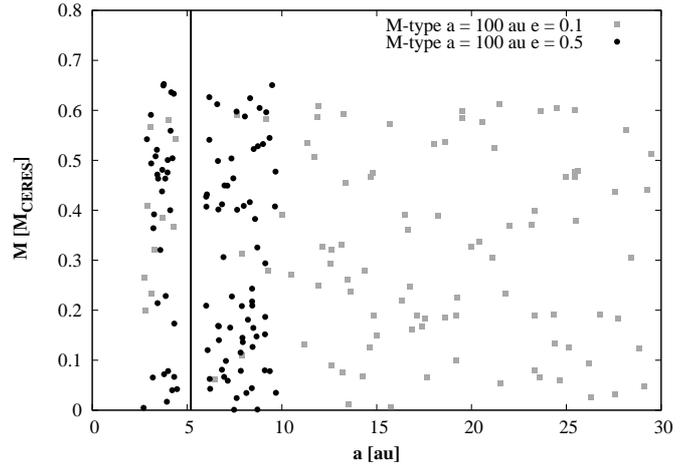
<sup>2</sup> 1 ocean =  $1.5 \times 10^{21}$  kg of  $H_2O$



**Fig. 1.** Collision scenarios resulting in a merge (a), a hit-and-run encounter (b) and erosion/mutual destruction (c). The diagrams show the masses of the ten largest fragments at the end of the simulation as percentages of the total system mass  $M_{\text{tot}} = 2$  lunar masses. The dashed horizontal line indicates the limit for significant fragments (see text).

particles. Our minimum and maximum mass are thus defined according to the fragments' mass after one impact. Therefore, members of our ring will have masses randomly and equally distributed between 0.1% to one Ceres' mass. The total mass of the ring of 10000 asteroids amounts to  $M_R = 0.5 M_{\oplus}$ . Thus the quantity of water, in terms of Earth-ocean units, available in a ring will be 200.

In each system, we defined the size of the disk of planetesimals by the following borders. As we focus on the transport of icy bodies, the inner border of the disk is set to the snow-line position [Lecar et al., 2006, Martin and Livio, 2012, 2013], border between icy and rocky planetesimals. Its position changes as the star's luminosity evolves during its birth phases. As our host star is a G2V type, we considered the inner border of the disk of planetesimals according to observations in the Solar System, suggesting the snow-line to be at  $\sim 2.7$  au. The outer border of the disk of planetesimals is influenced by perturbations induced by the secondary star. Since we consider initially circular motion for the planetesimals, the stability border depends mainly on three parameters: the mass ratio of the system,  $a_b$  and  $e_b$  [Rabl and Dvorak, 1988, Holman and Wiegert, 1999, Pilat-Lohinger and Dvorak, 2002]. These authors showed that it is possible to link these parameters to derive a critical semi-major axis  $a_c$  as the maximum initial semi-major axis for a particle to survive in the system. In contrast to Rabl and Dvorak [1988] and Holman and Wiegert [1999] who classified unstable orbits via ejections of test planets from the system, Pilat-Lohinger and Dvorak [2002] calculated the Fast Lyapunov Indicator (FLI) for each orbit to distinguish between stable and chaotic motion. This well known chaos detection method was introduced by Froeschlé et al. [1997]. In case of circular motion of the planets and the planetesimals, it is possible to use the study by Holman and Wiegert [1999] where  $a_c$  and its uncertainty  $\Delta a_c$  allows a good determination of the outer border (maximum semi-major axis allowed) for asteroids in the ring as  $a_c - \Delta a_c$ , which is in good agreement with the stability limits derived from FLI computations [Pilat-Lohinger and Dvorak, 2002]. Asteroids of our belt are randomly positioned between the inner (the snow-line) and and outer borders (the stability limit  $a_c - \Delta a_c$ ). Figure 2 shows a comparison of initial asteroid's mass distribution for a secondary M star at 100 au and  $e_b = 0.1$  and 0.5. The position of the gas giant planet is indicated by the vertical line. Because of the binary's tight periastris in the case of  $e_b = 0.5$ , the asteroid belt is less extended and exhibits a higher mass density. In order to prevent immediate dynamical instability, all bodies have been carefully placed so that their



**Fig. 2.** Example of mass distributions in the circumprimary ring as a function of the asteroids' semi-major axis under the gravitational influence of a secondary M star at  $a_b = 100$  au and  $e_b = 0.1$  ( $\blacksquare$ ) and  $e_b = 0.5$  ( $\bullet$ ). The vertical line refers to the gas giant's position. All particles are initially spaced by several Hill's radii to prevent immediate dynamical instability.

initial mutual separation were at least several Hill's radii.

In our main simulations, as we assume that the giant planet is already formed so that the remaining gas has been evaporated or coagulated into the asteroid belt, we do not take any effects related to gas drag into account (therefore no gas driven migration, no eccentricity damping). The initial eccentricities and inclinations are randomly chosen below 0.01 and  $1^\circ$  respectively. To avoid strong initial interactions with the gas giant, we assume that the giant planet has cleared a path in the disk around its orbit. The width of this gap is  $\pm 3R_{\text{HGG}}$  where  $R_{\text{HGG}}$  is the giant planet's Hill Radius<sup>3</sup>. Requiring orbital stability of the gas giant at 5.2 au reduces the number of possible binary configurations. Therefore, we excluded the case where  $a_c - \Delta a_c \leq a_{\text{GG}} + 3R_{\text{HGG}}$ . This results in a total number of 23 binary systems configurations that were studied in this work and summarized in Table 3.

We limited our study to 10 Myrs integration time. This is of course much shorter than the timescale of terrestrial plane-

<sup>3</sup> However, we did not exclude possible location of asteroids inside mean motion resonances (MMRs). Indeed, we assume that the presence of the gas might have kept asteroids on stable orbit inside MMRs. Then, the MMR perturbations became stronger when the gas vanished.

**Table 3.** Binary configurations studied in this article. Only the secondary stellar-type is reported.

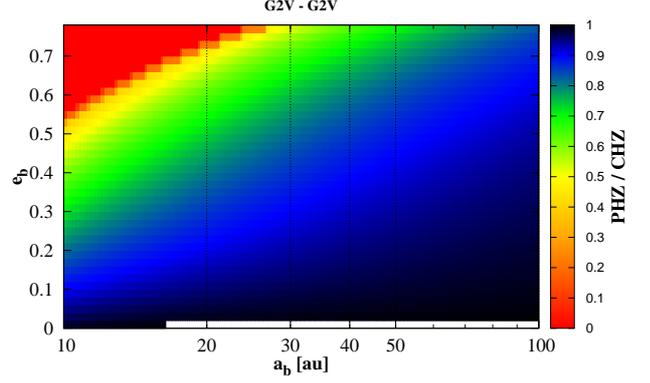
$e_b$ \ $a_b$ [AU]	25	50	75	100
0.1	K-M	G-K-M	G-K-M	G-K-M
0.3		G-K-M	G-K-M	G-K-M
0.5			M	K-M

tary formation ( $\sim 100$  Myrs) but as we make a comparison of many different binary star systems, we had to restrict this study to a shorter time. However, we will select from this study the most interesting systems for which a statistic over 100 Myrs will be made. We numerically integrated our systems using the *nine* package [Eggl and Dvorak, 2010] and only gravitational perturbations were taken into account. The numerical integrator used for the computations is based on Lie-series (see e.g. Hanslmeier and Dvorak [1984] and more recently Bancelin et al. [2012]). For a given configuration in Table 3, as our planetesimals do not interact with each other, the disk was divided into 100 subrings and separately integrated.

### 3. The Habitable Zone borders

As we study the flux of water-rich asteroids into the HZ, we need to know the position of this area. The definition, modeling and computation of the "classical HZ" (hereafter CHZ) is given in Kasting [1988], Kasting [1991], Kasting et al. [1993] and Kopparapu et al. [2013]. All these studies are based on a 1D cloud-free climate model, where the inner edge of the HZ is computed by increasing the surface temperature and the outer edge, by increasing the  $\text{CO}_2$  partial pressure (maintaining a constant surface temperature at 273 K). The corresponding stellar flux, needed to maintain the surface temperature, is then derived. Thus, these authors were able to express the CHZ borders as a simple fit function containing the stellar luminosity and temperature. Recently, Kopparapu et al. [2014] investigated the dependence of the HZ borders on the planetary masses and derived new coefficients for the computations of the effective solar flux. For a G star, the inner edge of the HZ corresponding to the runaway greenhouse limit is 0.950 au and the outer edge of the HZ corresponding to the maximum greenhouse is 1.676 au. The updated inner edge value is closer to the Sun than the one found by Kopparapu et al. [2013] because they used inputs from a 3D model by Leconte et al. [2013]. However, the exact value for the inner CHZ border depends on many assumptions and is still under discussion in current literature, [e.g. Wolf and Toon, 2014].

When including a binary companion in the system, the additional gravitational interaction and radiation can shrink the CHZ borders, as shown in Eggl et al. [2012] and Kaltenecker and Haghighipour [2013]. As a matter of fact, the smaller the periapsis of the binary, the more important the insolation of the primary, as the periapsis distance of the planet with respect to its host star can change significantly. In order to account for this effect, Eggl et al. [2012] introduced the so-called Permanently Habitable Zone (hereafter PHZ). The PHZ contains information on the planet's perturbed orbit. It serves as a mean to distinguish areas where a planet always receives the correct amount of insolation to remain habitable from regions where insolation conditions for habitability are only fulfilled



**Fig. 3.** PHZ/CHZ ratio as a function of the binary separation and the secondary's eccentricity. The red color indicates that the planet will always lie outside the PHZ borders. Only a graph for a secondary G star is represented as it is quite similar for a secondary K and M-types.

in an average<sup>4</sup> sense. Figure 3 shows the ratio PHZ/CHZ as a function of the binary's orbital elements ( $a_b, e_b$ ) for a G2V-G2V binary star system. The blue and black colors cover a large region where no or only minor differences between PHZ and CHZ were found. This means that the additional radiation from the second star is not enough to drastically cause a change of insolation at the surface of a planet. This is due to the fact that the secondary is too far or its periapsis too far away. For higher eccentricities, where the secondary's orbit approaches closer to the host star, the difference is increased (green color). The red color refers to regions where the PHZ vanishes either due to excessive insolation or due to orbital instability. It is clear that the truncation of the PHZ increases for large values of the periapsis of the binary companion. This is due to the fact that the stellar gravitational perturbations acting on the planet will cause a significant change of the planet's periapsis, which in turn influences the insolation at the planet's surface. A similar behavior is observed for K and M class secondaries as their mass does not significantly influence the PHZ/CHZ ratio. For our binary configurations, the difference between CHZ and PHZ is only of the order of 10% as shown in Table 4. As these values do not vary strongly with the secondary's mass, we did not report all 23 configurations.

## 4. Asteroid flux and water transport to the HZ

### 4.1. Statistics on the disk dynamics

During the simulation, each particle is tracked until the end of the integration time in order to assess the following numbers:

- asteroids crossing the HZ. They will be referred to as Habitable Zone crossers<sup>5</sup> (hereafter HZc). As we assume a two dimensional HZ, an asteroid will be considered as a HZc if the intersection point between its orbit and the HZ plane lies within the HZ borders.

<sup>4</sup> The planet's orbit is eccentric enough could leave the HZ from time to time.

<sup>5</sup> A HZc can cross several times the HZ before leaving the system or colliding with the stars or the planets

**Table 4.** PHZ borders given in au as a function of the binary orbital characteristics ( $a_b$ ,  $e_b$ ) used in our simulations. Compared to the CHZ borders (inner border is 0.950 au and outer border is 1.676 au), the PHZ intervals are smaller due to the additional radiation from the second star and eccentricity injected in the planet’s orbit.

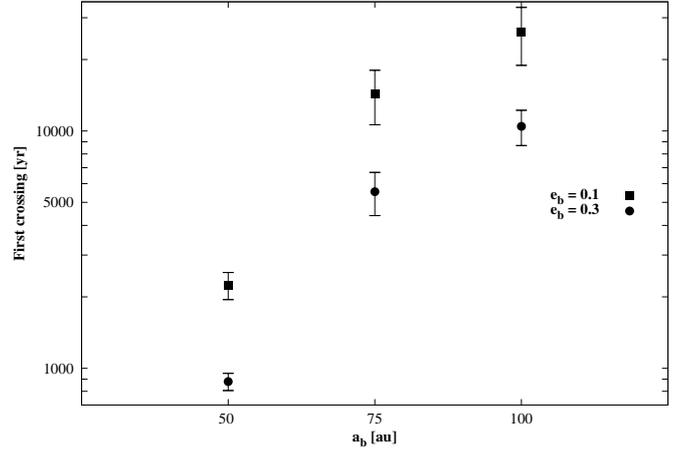
$e_b \backslash a_b$ [au]	25	50	75	100
0.1	[0.959:1.654]	[0.955:1.664]	[0.954:1.668]	[0.953:1.670]
0.3		[0.964:1.639]	[0.959:1.651]	[0.957:1.657]
0.5			[0.968:1.627]	[0.964:1.638]

- asteroids leaving the system when their semi-major axis  $\geq 500$  au
- asteroids colliding with the gas giant or the stars
- asteroids still alive in the belt after 10 Myr

Figure 4 shows the resulting statistics on the asteroids’ dynamics. It represents four panels corresponding to the secondary’s semi-major axis investigated. Each histogram shows the dynamical outcome of our asteroids expressed in terms of probability, as a function of the secondary’s eccentricity. Below 100%, the percentage of asteroids that are still present in the belt (“alive”), that were ejected or collided with the stars or the gas giant is shown. The black area of each histogram above 100% indicates the probability for asteroids to enter the HZ. Such asteroids, crossing the HZ, are called HZc. The perturbations due to both the gas giant and the binary companion can cause an increase in eccentricity of the asteroids within the planetesimal disk which of course depends on the binary configuration. A comparison of the different histograms indicates that the key parameter is the periapsis of the binary system which is defined by the eccentricity of the binary. Of course not only the asteroids are perturbed by the secondary, the gas giant at 5.2 au is also perturbed and its initially circular motion will change to an elliptic one. This behavior is highlighted by the increasing value of the probability to become a HZc if the secondary’s periapsis distance decreases and if its mass increases. Indeed, for a given value of  $a_b$  (for instance 50 au), one can see that this probability is at least doubled when  $e_b$  increases. As a consequence, the asteroid belt will be depopulated because of dynamically induced ejections as well as collisions with the giant planet and the stars. Because the rate of colliding and ejected asteroids is increased, a ring will be depopulated faster when  $e_b$  becomes larger. Therefore, the statistics in Fig. 4 shows that the probability for a member of the asteroid ring to stay in the system after 10 Myrs will decrease with the periapsis distance and the secondary star’s mass. Finally, these results can also answer the question of the presence of an asteroid belt in such systems. Indeed, if we assume that the gas could protect small bodies from secular resonances or mean motion resonances (MMRs), it is highly unlikely that they survived in binaries with small periapsis separation, after the gas has dissipated.

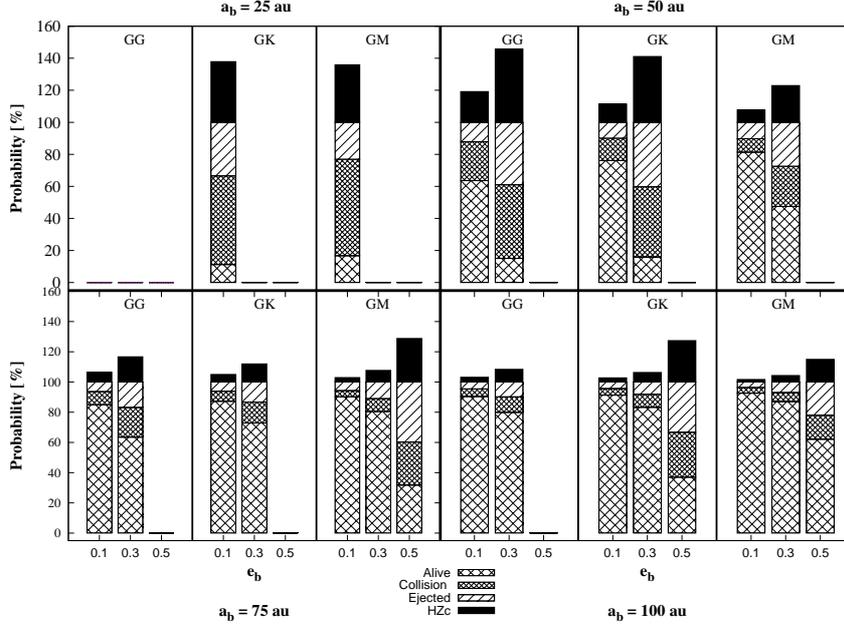
#### 4.2. Timescale statistics

Depending on the periapsis distance of the secondary, the disk of planetesimals can be perturbed more or less rapidly. As a matter of fact, asteroids will suffer from the gravitational perturbations of the secondary star and the gas giant, and their eccentricity may increase quickly. Figure 5 shows statistical results of the average time needed by an asteroid to become a HZc, i.e. the



**Fig. 5.** Median time for an asteroid to become a HZc for the case of a secondary G-type with  $e_b = 0.1$  (■) and  $e_b = 0.3$  (●). This corresponds to the time when an asteroid crosses the HZ for the first time. The statistics is made over the 10000 asteroids and the  $1\sigma$  value is represented by error bars.

time it takes to reach the HZ. This corresponds to the time spans until the first asteroid enters the HZ. The median value and its absolute deviation (error bars) are presented for a set of 10000 asteroids for the case of a secondary G-type with  $e_b = 0.1$  (■) and  $e_b = 0.3$  (●). This confirms a strong correlation between the periapsis distance and the time of first crossing. Figure 5 clearly shows that the average time varies from a few centuries to tens of thousands of years. The closer and more massive the secondary star, the sooner asteroids can reach the HZ. In contrast, the crossing timescale will become larger as the number of HZc increases as shown in Fig. 6. This parameter corresponds to the bombardment timescale, within 10 Myr of integration time, and is derived regarding the last crossing inside the HZ but regardless the asteroid’s water content. Indeed, once an asteroid becomes a HZc, it can cross the HZ several times as long as its orbit is stable and until it is ejected out of the system or collides with the giant planet or the stars. However, water-rich asteroids could be dry before this corresponding timescale, revealing that water transport could occur on a very short time (compared to planetary formation timescale). Besides, one can notice from Fig. 6 that most of the systems, with large  $a_b$  and low  $e_b$ , having low crossing timescales are also those where most asteroids remained in the after 10 Myrs as shown in Fig. 4. This suggests that asteroid flux to the HZ could occur in several steps as some asteroids need more time to drastically increase their eccentricity in order to be moved to lower orbits and reach the HZ. This reveals also that water sources can still be available in the ring, provided that asteroids still have icy water on their surface. This study would of



**Fig. 4.** Statistics on the disk of planetesimals dynamics. Each histogram shows the evolution (expressed in probability) of the asteroids in the ring within 10 Myr of integration. They can still be present in the system (“alive”), become a HZc, collide with the stars or the gas giant, or be ejected out of the system. The closer the secondary and the higher its mass, the higher the probability to empty the asteroids ring.

course require longer integration time  $> 10$  Myrs. Nevertheless, we have a clear guess on the efficiency of binary stars systems to transport asteroids from beyond the snow-line to the HZ on a short timescale.

### 4.3. Water transport statistics

Each HZc entering the HZ will bring a certain amount of water. However, regarding the integration timescale, the water content of asteroids may vary with time. Indeed, increased eccentricities can cause asteroids to approach close to the stars. This in turn would lead to a mass variation mainly due to a loss of their water content.

#### 4.3.1. The water mass loss process

To quantitatively assess the water content of asteroids, we followed their water mass fraction evolution throughout the simulations, including mass loss process, until they enter the HZ. The main mechanisms that can induce a relevant mass loss for active (comet-like) or inactive asteroids are ice sublimation and impact ejection [Jewitt, 2012]. The latter process occurs when smaller asteroids impact larger ones<sup>6</sup>. These impacts can be highly erosive due to characteristic speeds  $\sim 5 \text{ km.s}^{-1}$  [Bottke et al., 1994] and the ejected amount mass can be significant. However, typical impact events in the main-belt have an impact probability  $\sim 3.0 \times 10^{-8} \text{ km}^{-2}.\text{yr}^{-1}$  [Farinella and Davis, 1992]. Yet, according to Bottke et al. [2005], the timescale for an impact event to happen in our sample of asteroids belt (with radius from tens to hundreds of kilometers) is much longer than our integration time. Thus, we neglected this process in our study. The only mass loss

<sup>6</sup> Such impacts do not necessarily lead to a complete destruction or break-up of asteroids

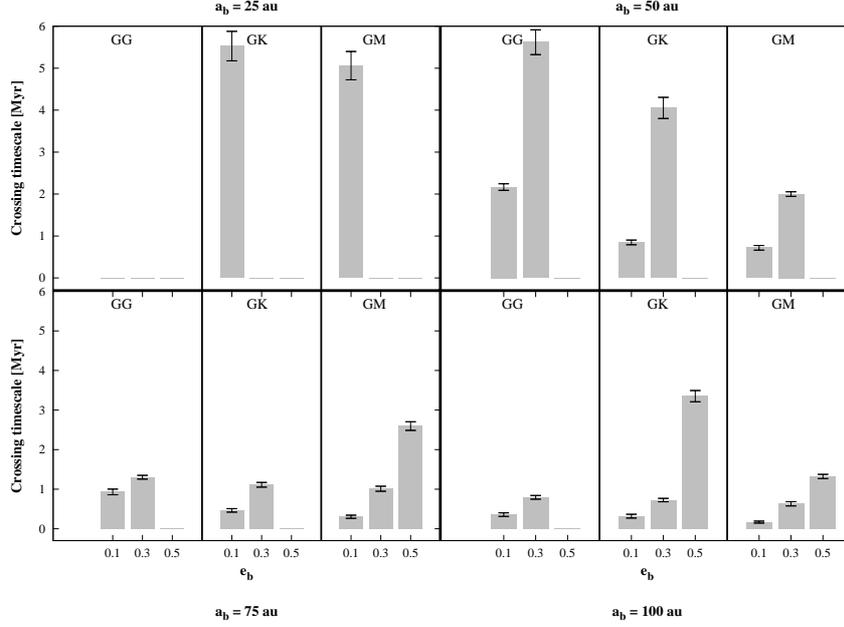
process we consider is due to ice sublimation when the asteroid comes relatively close to the star. This process can be stepped up in double star systems, especially when the companion is on an eccentric orbit. Even if the secondary is not particularly close, asteroids’ eccentricity can be pumped and they can receive a large amount of insolation. Therefore, the water mass loss rate  $\dot{m}$  was computed accounting for the radiation of both stars. The estimation of  $\dot{m}$  can be derived by solving a balance energy equation between the net incoming stellar flux, the ice sublimation and the thermal re-radiation<sup>7</sup>, as expressed in Eq. (1)

$$\sum_{i=1}^2 \frac{F_{\star,i}(1-A_i)}{R_i^2[\text{au}]} \cos\theta_i = \epsilon\sigma T^4 + L(T)\dot{m}(T) \quad (1)$$

where

- $F_{\star}$  is the stellar constant and is computed as  $F_{\star} = F_{\odot} L_{\star}$  ( $F_{\odot} \sim 1360 \text{ W.m}^{-2}$  is the solar constant).
- $A$ , the bound albedo, product of the geometric albedo and the phase integral, defines the fraction of the total incident stellar radiation reflected by an object back to space. Asteroids can have  $A \approx 0.5$  but most of them have relatively low albedo [Shestopalov and Golubeva, 2011]. Ice material is known to be a good radiation reflector. In order to maximize  $\dot{m}$ , we will follow the approach of Jewitt [2012] considering our objects with dirty ice material with low albedo because clean ice sublimates too slowly at main-belt distances. Therefore, we used an averaged albedo  $A_1 = A_2 = \bar{A} = 0.05$ .
- $R$  is the distance to the star (primary or secondary) expressed in au
- $\theta$  is the angle between the incident light and the normal to the the asteroid’s surface. According to Jewitt [2012],  $\dot{m}$  is weaker for an isothermal surface than at the sub-solar point

<sup>7</sup> assuming the asteroid to have black body properties



**Fig. 6.** Crossing timescale expressed in Myr. It corresponds to the last crossing inside the HZ. Up to 6 Myr for the most perturbed systems but also with the lowest number of asteroids still present in the system within 10 Myr of integration time. For the other systems, the crossing timescale is much lower because their belt still contain a huge number of "alive" asteroids. Indeed, the dynamics of the system needs more time to empty the asteroid belt population.

of a non-rotating body. Again, to maximize  $\dot{m}$ , we consider the sub-solar case with  $\theta = 0^\circ$ .

- $\epsilon$  is the emissivity of the surface,  $\epsilon \sim 0.9$
- $\sigma = 5.67 \times 10^{-8} \text{ W.m}^{-2}.\text{K}^{-4}$  is the Boltzmann constant
- $T$  is the equilibrium temperature at the surface expressed in K
- $L$  is the latent heat of sublimation in  $\text{J.kg}^{-1}$
- $\dot{m}$  is the surface mass loss rate in  $\text{kg.m}^{-2}.\text{s}^{-1}$

$\dot{m}$  can be obtained by computing the temperature  $T$  solving Eq. (1). To this purpose, we expressed all the variable parameters as a function of  $T$ . According to Delsemme and Miller [1971],  $\dot{m}$  can be written as:

$$\dot{m} = P_s \sqrt{\frac{\mu}{2\pi kT}} \quad (2)$$

where  $\mu = 18 \text{ g.mol}^{-1}$  is the water molar mass and  $P_s$  is the saturation pressure and defined by the empirical formula:

$$\log P_s = 4.07023 - \frac{2484.986}{T} + 3.56654 \log(T) - 0.00320981 T \quad (3)$$

Finally, the latent heat is expressed as:

$$L(T) = 2834.1 - 0.29(T - 273.15) - 0.004(T - 273.15) \text{ J.g}^{-1} \quad (4)$$

#### 4.3.2. The water mass fraction of incoming HZc

The value of  $\dot{m}$  is constantly updated during the simulations and the accumulated surface mass loss  $dm$  reads:

$$dm = \sum \dot{m} \Delta t \quad \text{kg.m}^{-2} \quad (5)$$

where  $\Delta t$  represents the time elapsed since the beginning of the integration. We then compute the sublimating area  $4\pi r^2$  with  $r$

the radius of the HZc. If we consider the following density for water ice shell and a basalt core, respectively  $\rho_i = 900 \text{ kg.m}^{-3}$   $\rho_c = 3000 \text{ kg.m}^{-3}$ , then for a given wmf, the mean density of an asteroid is

$$\bar{\rho} = (1 - \text{wmf})\rho_c + \text{wmf} \times \rho_i$$

Therefore

$$r = \left( \frac{3m}{4\pi\bar{\rho}} \right)^{1/3}$$

with  $m$  the mass of the asteroid. Thus we can derive the total water mass loss in kg  $\Delta m = dm \times 4\pi r^2$ .

Whenever an asteroid becomes a HZc i.e. when it first enters the HZ, we suppose that its current water content will be delivered. This is the best case scenario as the total water content of the HZc corresponds to the maximum amount of water available in the HZ. In reality, however, only a small fraction of water would be accreted onto a planet (or planetary system) inside the HZ. Indeed, both the real position of the planet on its orbit and the impact velocity of these HZc are key parameters in collisional material transport as pointed out by Thébault et al. [2006] and Leinhardt and Stewart [2012]. A fully self consistent modeling of the water delivery at impact lies beyond the scope of the current work, however. Hence, we aim to study the amount of water transported into the HZ rather than the amount of water accreted by a planet therein. Figure 7 shows the total amount of water that was transported into the HZ (expressed in terrestrial oceans units) as a function of the binary system characteristics. Each histogram represents the total amount of oceans ending in four partitions of the HZ. They correspond to equally spaced rings using the values obtained in Table 4. Therefore we define the inner HZ border (closest ring to the PHZ inner border value), Central 1 and 2 (intermediate borders) and Outer HZ (closest ring to the PHZ outer border value). We

also illustrated on this figure, the additional quantity of water transported between the inner edge  $A$  [ $CHZ(A)$ ;  $PHZ(A)$ ] and the outer edge  $B$  [ $PHZ(B)$ ;  $CHZ(B)$ ] of the HZ (gray color and refereed as "additional").

The main results suggested by this figure are:

- a) one can see that a maximum of 70 oceans can be transported into the CHZ. Note that 70 oceans represents 35% of the total number of oceans contained in the 10000 asteroids population<sup>8</sup>. Variances are large, however. One of the reasons for the large spread in the amount of transported water is the short simulation time. This introduced a bias towards systems where the water transport is fast. In other words, the seemingly small amount of transported water in some of the presented systems does not imply that their HZs have to remain dry. It merely highlights the fact that the delivery process would require a longer time as many asteroids are still present in the system after 10 Myrs of integration time (see Figure 4). However, these results show how fast and efficient are some systems to transport water.
- b) the difference between the water transported in CHZ and PHZ (gray color) is not that significant compared to the total number of incoming oceans. Indeed, the difference does not exceed  $\sim 3$  oceans. One should note that we disregarded large orbital variations of any embryos located in the HZ caused by the perturbed motion of the gas giant because of the presence of the secondary star. This in turn can perturb the motion on any planets in the HZ<sup>9</sup>. However, according to Williams and Pollard [2002], an average insolation – covering almost the entire CHZ – is sufficient to retain liquid water on an Earth-twin surface and secure the habitability of planets.
- c) any binary star systems is efficient enough to produce a flux of asteroid within the whole HZ and thus to make water sources available for embryos lying there. However, we can see that statistically, most of the water ends in the outer HZ. This is due to the fact that its surface area is much more wider than the other rings and the probability for an asteroid to fell in the outer HZ is higher. One can notice that the quantity of water brought into the outer HZ versus the other cells is quite balance. Indeed, regarding the definition of a HZc, we expect asteroids on inclined orbits not to necessarily cross the outer HZ. Besides, dynamical studies suggest that secular perturbations can lie inside the HZ or beyond the snow-line, depending on the binary systems' characteristics [Bancelin et al., 2015, Baszó et al., 2015, Pilat-Lohinger et al., 2015]. In addition, depending on the secondary's periapsis, the secondary will shorten the lifetime of particles inside MMRs [Bancelin et al., 2015]. Therefore, for asteroids initially orbiting inside MMRs and/or secular perturbations, the dynamical evolution can be violent and their orbit crossing the HZ will not necessarily be from the outer HZ to the inner HZ.

#### 4.4. Influence of the initial water content

Let us now compare the water transport efficiency when the initial wmf is not equally distributed throughout the asteroid belt. The equal water distribution model will be called  $WMF_A$ . Observations in the main-belt [Abe et al., 2000, DeMeo and Carry, 2014] suggest that a gradient exists in the chemical composition of the asteroids. Besides, we expect distant asteroids, up to the Kuiper-belt distance, to have a higher wmf than asteroids in the main-belt. Thus, we modeled – we called this model  $WMF_B$  – the wmf distribution as a linear function of the distance to the central star, fulfilling the following boundary conditions: the upper limit is fixed at 20% of water for asteroids at 30 au<sup>10</sup>. To find the lower limit for asteroids at 2.7 au, we follow Raymond et al. [2004] and Haghhighipour and Raymond [2007] assuming a wmf  $\sim 5\%$ . Under these assumptions, a belt in tight binary systems will have a lower water mass ratio than a belt under the influence of a secondary on a low eccentric orbit. Indeed, the ratio between model  $WMF_B$  and  $WMF_A$  gives lower limits of 0.62, 0.58 and 0.63 respectively for G, K and M secondary stars. When the secondary's periapsis increases, we get upper limits of 1.07, 1.18 and 1.27 respectively. However, the quantity of oceans transported to the HZ using  $WMF_B$  does not exceed  $2/3$  of the amount of transported water when using  $WMF_A$ , even if the belt initially contains more water. This shows that:

- a) our results are robust
- b) asteroids closer to the snow-line are more likely to become HZc. As a matter of fact, according to model  $WMF_B$  asteroids will contain 10 % of water if they are located below 11 au<sup>11</sup>. If asteroids becoming HZc were initially beyond this distance, we would have had an equivalent or higher number of transported oceans.

## 5. Comparison with a single G star system

In this section, we will compare the water transport efficiency between binary and single star systems. To this purpose, we considered the same initial conditions for the gas giant and the asteroid belt distribution, except that we only have a single G star in our dynamical system. As the comparisons are made for the same asteroids' initial conditions, we have to consider, for the single star system, the same size for the disk, given by the binaries' characteristics. This is why, in Fig. 9, results for the reference single star case are different depending on the values of the binary's eccentricity and separation.

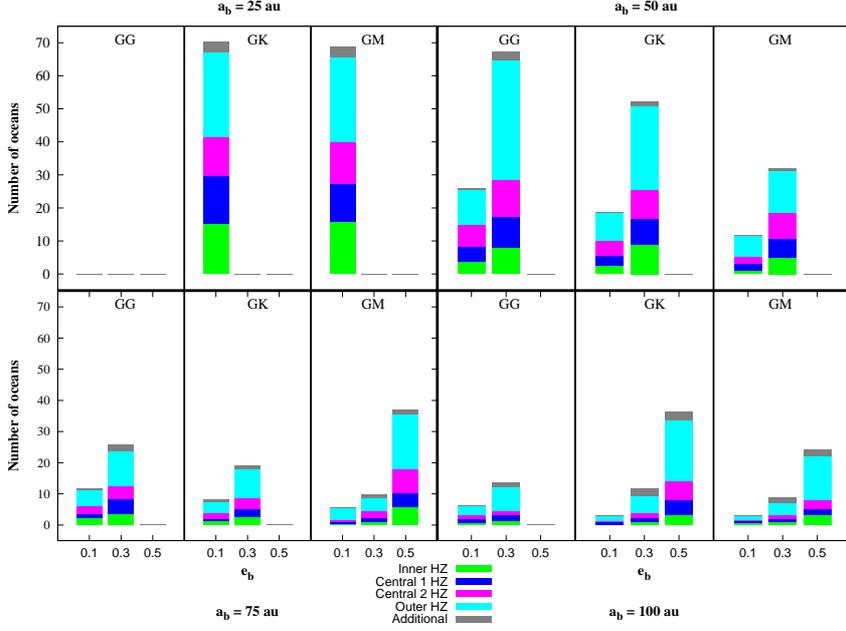
For computational reasons, our comparison is limited to a G2V-G2V-type binary. Besides, regarding Fig. 6, there is no more crossings in the HZ after 5 – 6 Myr. Therefore, the number of oceans brought to the HZ will not vary after this time. Thus, each system was compared at equivalent integration times ( $\leq 5$  Myr). Our results show that an asteroid that was initially in the ring will need 2 – 20 times longer to reach the HZ in a single star system. That is, because the asteroid belt is not perturbed strongly enough by the gas giant to produce a large asteroids flux towards the HZ as shown in Fig. 8: the presence of the secondary star can put asteroids with initial semi-major axis  $a_0$ , on high eccentric orbits, i.e. very low periapsis distance  $q_{HZc}$ . This

<sup>8</sup> 200 oceans contained in this population

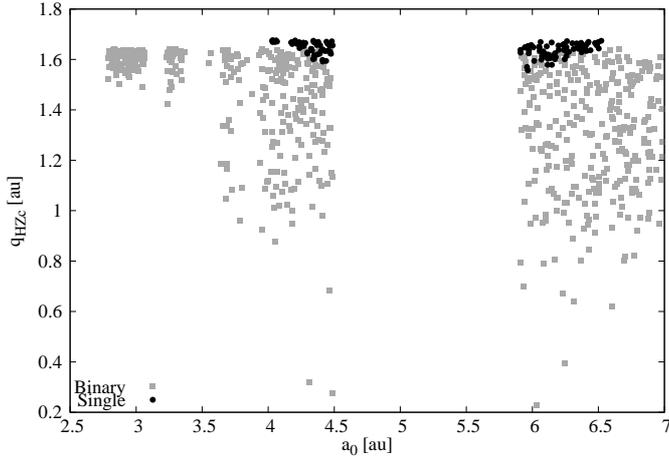
<sup>9</sup> when including a gas giant in a binary star systems, its additional perturbation will increase the eccentricity on any planets located in the HZ

<sup>10</sup> As shown in Figure 2, our objects' semi-major axis does not go beyond 30 au

<sup>11</sup> provided that the critical semi-major axis criteria allows asteroids to be located beyond this distance



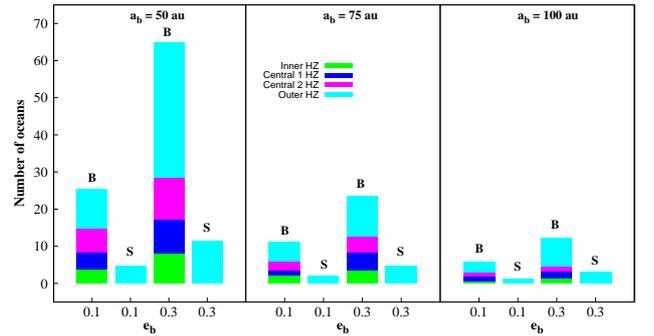
**Fig. 7.** Total number of oceans transported by all the HZc when they first cross the HZ. The color code is related to four equally spaced rings of the HZ: inner, central 1 and 2, outer HZ (see text). We also indicated the equivalent number of additional ocean crossing the truncated CHZ interval when the dynamics of the secondary star is not taken into account for the computation of the HZ borders.



**Fig. 8.** Initial semi-major axis  $a_0$  and final periapsis distance  $q_{\text{HZc}}$  of the incoming HZc for a single ( $\bullet$ ) and binary ( $\blacksquare$ ) star system.

will result in a faster depletion of the belt and a shorter bombardment duration, compared to a single star system.

Consequently, the probability for an asteroid to cross the HZ will be  $\sim 4 - 6$  times higher in a binary star system. Note that the number of scattered incoming asteroids mainly increases because the secondary star perturbs the giant planet's orbit. As the flux of asteroids is less efficient in a single star system, the amount of water brought to the HZ is smaller. In fact, the water transport is  $4 - 5$  times less efficient without a second star. Finally, Fig. 9 compares the amount of delivered water in various systems. Histograms marked with the letter *B* refers to binary star systems, those with letter *S* to single star systems. The color code indicates the amount of water that ended up in four equally spaced sub-rings (Inner, Central 1, Central 2, Outer) of the corre-



**Fig. 9.** Comparison of the water transport in single star (S) and binary star (B) systems. We restricted this study to binaries with two G-type stars. The various panels correspond to different semi-major axis of the secondary:  $a_b = 50 - 75 - 100$  au. The color code refers to different sub-rings of the HZ (see text). Note that, the two results for each panel account for different initial asteroid belt distributions (depending on  $e_b$ ), taken as the same for (S) and (B).

sponding PHZ (see Table 4). For a single star system, each ring of the CHZ is computed using the inner edge value 0.950 au and outer edge value 1.676 au. It is not surprising that the outer HZ is the most crossed ring. Indeed, its area is much larger than the other rings. This figure also highlights the fact that in such single star systems, hosting only one giant planet, basically all the water is transported in the outer HZ because the perturbation is not strong enough to drastically increase the eccentricity of any asteroid in the belt. In any case, these results show the efficiency of a binary star to transport water in the entire HZ over a shorter timescale compared to a single star system.

## 6. Summary and conclusion

In this work, we investigated the influence of a secondary star on the flux of asteroids to the Habitable Zone (HZ) over 10 Myrs of integration time. We estimated the quantity of water brought by asteroids located beyond the snow-line into the HZ of various double stars configuration (separation, eccentricity and mass of the secondary). An overlap of perturbations from the secondary and the giant planet in the primordial asteroid belt causes rapid and violent changes in the asteroids' orbits. This leads to asteroids crossing the HZ soon after the gas in the system has dissipated and the gravitational dynamics become dominant. Our results point out that binary systems are more efficient for water transport into the HZ, compared to a single star system. Not only asteroids flux is 4 – 6 times higher when a secondary star is present, but also the amount of transported oceans to the HZ can be 4 – 5 times more important, providing other water sources to embryos, in the whole HZ, in the late phase of planetary formation. Our results stress the fact that some systems can complete their water transport in a short time (~ 6 Myr), in contrast to single star system. Finally, our study can give a clear guess on the dynamics and the stability of objects moving under the perturbations of a binary star system and a gas giant. Indeed, as the depletion of an asteroid belt in binaries with small periapsis separations is faster, only a few small bodies will remain member of this belt. Thus, it would be unlikely to observe such an asteroid belt in such systems.

It is clear that dynamics in single and binary systems are completely different as the presence of the secondary together with a gas giant would directly have an impact on the dynamics of an asteroid belt but also on any planets or embryos located in the HZ. Indeed, similarly to the work of Pilat-Lohinger et al. [2008], secular perturbations and MMRs' intensity will depend on the secondary's orbital parameters and mass, which will be the purpose of a future study.

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