Part III

Dynamical Aspects of Icy Bodies. The Oort Cloud

Icy Bodies of the Solar System
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Galactic environment and cometary flux from the Oort cloud

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Abstract. The Oort cloud, which corresponds to the furthest boundary of our Solar System, is considered as the main reservoir of long period comets. This cloud is likely a residual of the Solar System formation due to the gravitational effects of the young planets on the remaining planetesimals. Given that the cloud extends to large distances from the Sun (several times 10 000 AU), the bodies in this region have their trajectories affected by the Galactic environment of the Solar System. This environment is responsible for the re-injection of the Oort cloud comets into the planetary region of the Solar System. Such comets, also called "new comets", are the best candidates to become Halley type or "old" long period comets under the influence of the planetary gravitational attractions. Consequently, the flux of new comets represents the first stage of the long trip from the Oort cloud to the observable populations of comets. This is why so many studies are still devoted to this flux.

The different perturbers related to the Galactic environment of the Solar System, which have to be taken into account to explain the flux are reviewed. Special attention will be paid to the gravitational effects of stars passing close to the Sun and to the Galactic tides resulting from the difference of the gravitational attraction of the Galaxy on the Sun and on a comet. The synergy which takes place between these two perturbers is also described.

Keywords. celestial mechanics, comets: general, Oort Cloud, solar system: general

1. Introduction

The first person who proposed the existence of a cloud of objects surrounding the Solar system was Öpik (1932). Studying the gravitational influence of the passing stars on very elongated orbit around the Sun as those of comets and meteors, he showed that their mean effect was to increase the perihelion distance. Because these orbits are prevent from any planetary perturbations once their perihelion has been raised enough, a cloud of objects at more than 10 000 AU might exist. From this preliminary study, Öpik concluded, however, that such cloud is likely not observable because of the preference of stellar perturbations to rise the perihelion rather than to decrease it.

Later on, looking at the original semi-major axis of 19 well observed long period comets, Oort (1950) showed that the orbital energy of these comets picked toward zero, with semi-major axes between 50 000 and 100 000 AU: the *Oort peak*.

Oort argued that these comets were entering the planetary region of the Solar System for the first time, and should form a reservoir surrounding the Sun between 10^4 and 10^5 AU : the *Oort cloud*. As Öpik, Oort took into consideration the effects of passing stars on elongated orbits. However, he noticed that these perturbations were able to move the perihelion of an Oort cloud comet close enough to the Sun for the comet to be observable.

More generally, at such distance from the Sun the Galactical environment of the Sun is able to modify the heliocentric trajectories of the Oort cloud comets. The present review is dedicated to the effects of these *external perturbers* on the flux of Oort cloud comets.

The estimation on population, shape and size of the Oort cloud will be first given in Sec. 2. Then, in Sec. 3 the three main external perturbers will be described: the passing stars (Sec. 3.2), the giant molecular clouds (Sec. 3.3) and the Galactic tides (Sec. 3.4). The efficiency of each perturber may be evaluated using a tool called the *loss cone* defined in Sec. 3.1. Section 4 is devoted to the synergy between the passing stars and the Galactic tides. The conclusions are given in Sec. 5.

2. Size, population and shape of the Oort cloud

The main goal of any study on the cometary flux from the Oort cloud is: how does the Oort cloud look like? Indeed, being not directly observable from Earth, one has to deduce the informations from the few comets which come close enough to the Sun to be observed.

One has to make a distinction between an inner Oort cloud, and the observable Oort cloud. No strict definition of these regions exists in the literature, however the following definitions may be acceptable. The inner border of the *inner Oort cloud* is the threshold from which the time scale for the Galactic tide to change the perihelion distance of a comet becomes comparable to the time scale for the planets to change its orbital energy (Duncan *et al.* 1987); and the inner border of the observable region of the Oort cloud - also called *outer Oort cloud* - is the threshold from which the Galactic tides are able to move the perihelion of a comet from outside the planetary region of the Solar system to inside the orbit of Jupiter in less than one orbital period. Both frontiers depend on the parameters used, however from numerical experiments (*e.g.* Duncan *et al.* 1987; Dones *et al.* 2004), the inner border of the Oort cloud should be around $a \sim 3\,000$ AU, and the inner border of the observable Oort cloud around $a \sim 20\,000$ AU. From now on, the region with $3\,000 < a < 20\,000$ AU will be called the inner Oort cloud, and the region with $a > 20\,000$ AU the outer Oort cloud. An innermost cloud, with $a \lesssim 3\,000$ AU, may also be defined (Brasser 2008).

The size. The parameter which is the easiest to obtain, *a priori*, is the size of the Oort cloud. Indeed, it is enough to reconstruct the original semi-major axis of the observed comets, *i.e.* the semi-major axis before the comet enters the planetary region of the Solar System. This method allows mainly to deduce the size of the outer Oort cloud. This was made by Oort (1950), and he concluded that the Oort cloud should be at heliocentric distance between 50 000 and 150 000 AU. It appeared, however, that the non gravitational forces induced by the out-gazing of a comet when it is close to the Sun, change the determination of the original semi-major axis. Using a set of long period comets with large perihelion distance for which non-gravitational forces are weak, Marsden & Sekanina (1973) showed that the Oort peak is rather around 25 000 AU. A more recent study made by Królikowska (2006) gives an even smaller value with a peak around 17 000 AU but with a more spread distribution.

The population. Among the parameters which defined the Oort cloud, its population is probably the most important. Indeed, this parameter constrains the scenarios of the formation of the solar system. The population of the cloud may be estimated only by numerical experiments and making comparison with the observations. Consequently, one is mainly able to evaluate the population of the outer Oort cloud. The more recent estimates of these population range between 5×10^{11} and 50×10^{11} (Weissman 1996; Emel'yanenko *et al.* 2007). As regards the inner Oort cloud, it is supposed to be from 1 (Dones *et al.* 2004) to 4 times (Duncan *et al.* 1987) the population of the outer Oort cloud. These estimations are however uncertain because of the difficulty to evaluate the absolute magnitude of a comet. Using an averaged comet mass of 4×10^{16} g, Weissman (1996) estimated the mass of the outer Oort cloud from 6 to 7 Earth masses, however this quantity is poorly constrained.

The shape. The orientation of the perihelion of the observed long period comets does not show a clear preference (even if some gathering might be observed, but this point will be discussed later). Oort (1950) and Yabushita *et al.* (1982) showed that the distribution of the heliocentric velocity of Oort cloud comets with semi-major axis greater than 20 000 AU should be isotropic, with an eccentricity distribution function proportional to the square of the eccentricity (Hills 1981). Numerical experiments showed that the threshold from which the Oort cloud becomes isotropic is rather at $a \sim 10\,000$ AU. For smaller heliocentric distances, the orbit planes should concentrate around the ecliptic (*e.g.* Levison *et al.* 2001; Emel'yanenko *et al.* 2007), keeping a memory of their origin. The density profile of the heliocentric distance for the outer Oort cloud, may be obtained only from numerical experiments of the Oort cloud formation. Such a problem is out of the scope of the present review. However, all the studies seem to agree for a density profile $n(r) \propto r^{-s}$ with $s \sim 3.5$ (Duncan *et al.* 1987; Dones *et al.* 2004; Brasser *et al.* 2006; Emel'yanenko *et al.* 2007).

3. The external perturbers

3.1. *The loss cone*

When a quasi parabolic comet enters the planetary region of the Solar System, its trajectory will be affected by the planets. The Fig 1 (From Fernández 1981) shows the typical energy change of a comet passing through the planetary region of the Solar System versus the perihelion distance for 6 different ranges of initial inclination. The figure hilights a property already used by Oort (1950) and Weissman (1980) among others: a comet with a perihelion distance smaller than $10 - 15$ AU will be likely removed from the Oort cloud by planetary perturbations, being sent on a more tidily orbit to the Sun or ejected from the Solar System. This consideration allows Oort to postulate that the observed long period comets in the Oort peak are new. Because the perturbations are mainly due by Jupiter and Saturn, the threshold around 15 AU has been called the *Jupiter-Saturn barrier.*

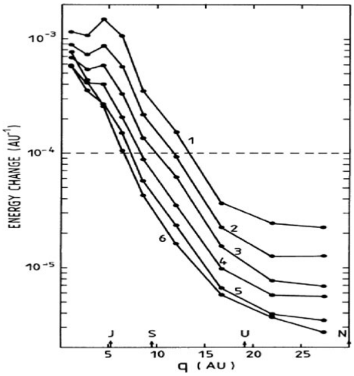

Figure 1. Typical energy change of comet passing through the planetary region as a function of its perihelion distance q. Each curve corresponds to a certain range of inclinations such that: curve 1 for $0° < i < 30°$, ..., curve 6 for $150° < i < 180°$. Credit: Fernández, A&A, 96, 26, 1981, reproduced with the permission of © ESO.

Now, for quasi-parabolic ($q \ll r$) comets, one has:

$$v_t = \frac{\sqrt{2\,\mu\,M_\odot\,q}}{r}, \tag{3.1}$$

where v_t is the tangential velocity of the comets, r the heliocentric distance, q the perihelion distance, μ the universal gravitational constant and $M_\odot$ the mass of the Sun.

The Jupiter-Saturn barrier may be modelled by a tangential velocity $v_t = \sqrt{2\mu M_\odot 15}/r$, which defines a cone with decreasing width, given by v_t, for increasing heliocentric distance. Inside the loss cone, an observable cone may be defined in a similar way, by a perihelion distance equal to 5 AU for instance (Oort used 1.5 AU).

Just outside the planetary region going away from the Sun, the loss cone is empty. To observe a flux of comets from the Oort cloud, the loss cone on the way inward to the Sun has to be filled such that the observable cone contains also some comets. For such event to occur, the external perturbers, *i.e.* passing stars, Galactic tides, giant molecular clouds, must fill completely the loss cone.

An external perturber affects mainly the angular momentum of a comet, *i.e.* its tangential velocity v_t. The typical perturbation of v_t increases with the heliocentric distance, which defines also a cone: the *smear cone* (Hills 1981). The efficiency of an external perturber is at its maximum when the size of its smear cone becomes greater than the size of the loss cone. Indeed, for such, or greater, heliocentric distances the loss cone, and consequently the observable cone, are filled completely. Thus the flux of Oort cloud comets may be directly estimated by the size of the observable cone.

Preliminary experiments have shown that the stars are able to filled completely the loss cone when $r > 50\,000$ AU (Oort 1950; Rickman 1976). We will now discuss in more detailed the efficiency and characteristics of each external perturber.

3.2. *The passing stars*

Once in the Oort cloud, since the comets are far from the Sun, Oort considered that only perturbations from random passing stars, can change significantly the angular momenta of comets and send some of them into the loss cone. From this time, and for more than three decades, stellar perturbations were almost the only mechanism considered to produce observable comets. Many studies were devoted to this transport (e.g. , Rickman 1976; Weismann 1979; Fernández 1980; Hills 1981; Remy & Mignard 1985).

It appeared from all the experiments that this flux may be divided into two components: *(i)* a quasi constant background flux from the outer part of the cloud (Rickman 1976; Hills 1981; Heisler *et al.* 1987), *(ii)* a sporadic flux characterised by eventually strong comets showers extending toward the inner Oort cloud (Hills 1981). The former is due by frequent stellar encounters at large heliocentric distances filling the loss cone at any time; whereas the latter is due by rare but close stellar encounters able to fill temporally the loss cone at small heliocentric distance, depending on the impact distance of the star with the Sun.

This phenomenon is illustrated in Fig. 2 (from Heisler *et al.* 1987), where the flux of comets at heliocentric distance smaller than 10 AU per period of 10^6 yr for three different values of initial semi-major axis versus time is given. One observes: *(i)* for $a_0 = 10\,000$ AU, few but very strong comets showers, *(ii)* for $a_0 = 30\,000$ AU, a background flux with large fluctuations due to comets showers and *(iii)* for $a_0 = 40\,000$ AU, the loss cone is always filled yielding an almost constant background flux.

Some studies were devoted to the problem of determining whether or not we are experiencing a comets shower caused by a recent close stellar encounter with the Sun. Dybczyński (2002) has shown that such encounter should induce a strong asymmetry

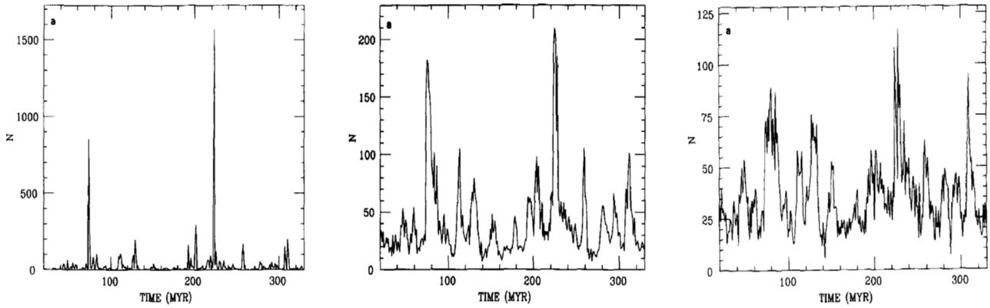

Figure 2. Number of comets per million years than pass through a perihelion less than 10 AU and have initial semi-major axis $a_0 = 10\,000$, $30\,000$ and $40\,000$ AU, from left to right. From Heisler *et al.* (1987).

in the distribution of the aphelion direction of the comets directly injected by the passing star, the asymmetry being characterised by an accumulation of perihelion direction toward the anti-perihelion direction of the stellar path.

Because the distribution of perihelion directions of the observed long period comets does not show any accumulation consistent with a recent stellar encounter it has been concluded that we are not experiencing a comets shower.

3.3. *The giant molecular clouds*

When the Solar System travels around the Galactic centre, it may also encounter some molecular clouds. These objects may be huge ($\gtrsim$20 pc) and massive ($\sim 5 \times 10^5\ M_\odot$). However, these quantities as well as the structure of a giant molecular cloud are poorly defined. The preliminary studies have shown that an encounter with a giant molecular cloud would have devastating effects on the Oort cloud (Biermann 1978) and that only the inner part of the Oort cloud could survived (Napier & Staniucha 1982; Clube & Napier 1982; Bailey 1983). Hut & Tremaine (1985) were less dramatic and showed that 2/3 of the comets should survived at 25 000 AU, with a destructive effect comparable to that of passing stars. A recent work by Jakubík & Neslušan (2008) shows that one should have a maximal erosion of the outer part of the cloud with 22% of the comets ejected.

The main conclusion one may retain from these studies is that the outer part of the Oort cloud is likely not primordial. However, because these encounters are difficult to model and should consist in rare event during the life of the Solar system (Bailey 1983), it has been of common use not to take them into account, even on long time span simulation.

3.4. *The Galactic tides*

The first time that the Galaxy was taken into account in the frame of Oort cloud comets dynamics, it has been modelled as a point mass (Chebotarev 1964, and Byl 1983). Later, in 1984-1986, the tides induced by the Galactic disk was also introduced in a series of papers (*e.g.*, Smoluchowski & Torbett 1984; Morris & Muller 1986; Byl 1986). It turned out that this *normal component* to the Galactic disk was very efficient to change the perihelion distance of an Oort cloud comet in one orbital period.

Nowadays, the Galactic tides model commonly used is the one defined by Heisler & Tremaine (1986) where the tides are supposed to be axisymmetric and the Sun moving on a circular orbit around the Galactic centre in the Galactic plane.

The particularity of the dynamics generated by the Galactic tides is that it is completely integrable when two approximations are made: *(i)* neglecting the *radial component*, *i.e.* the component of the tides which lies in the Galactic disk, with respect to the normal one (the common used values shows that there is almost one order of magnitude between the two components, see Levison *et al.* 2001); and, *(ii)* averaging the equations of motion with respect to the mean anomaly of the comet (Heisler & Tremaine 1986; Matese & Whitman 1989, 1992; Breiter *et al.* 1996; Breiter & Ratajczak 2005). In this case, the equations of motion write:

$$\left\langle \frac{\mathrm{d}G}{\mathrm{d}t} \right\rangle = -\mathcal{G}_3 \frac{5L^2}{4\mu^2} \left(L^2 - G^2\right) \left(1 - \frac{H^2}{G^2}\right) \sin 2g, \tag{3.2}$$

$$\left\langle \frac{\mathrm{d}g}{\mathrm{d}t} \right\rangle = \mathcal{G}_3 \frac{L^2 G}{2\mu^2} \left[1 - 5\sin^2 g \left(1 - \frac{L^2 H^2}{G^4}\right)\right], \tag{3.3}$$

where $L = \sqrt{\mu a}$, $G = \sqrt{\mu a(1-e^2)}$, $H = \sqrt{\mu a(1-e^2)}\cos i$, e is the comet eccentricity, i and g are the comet inclination and argument of perihelion with respect to the galactic plane respectively, and $\mathcal{G}_3 = 4\pi\mu\rho_0$, where $\rho_0 = 0.1\, M_\odot \mathrm{pc}^{-3}$ is the density of the Galactic disk in the solar neighbourhood (Levison *et al.* 2001).

Figure 3 shows the dynamics in the $(g - G/L)$ space generated by Eqs. 3.2 and 3.3, with $|H|/L = 0.585$.

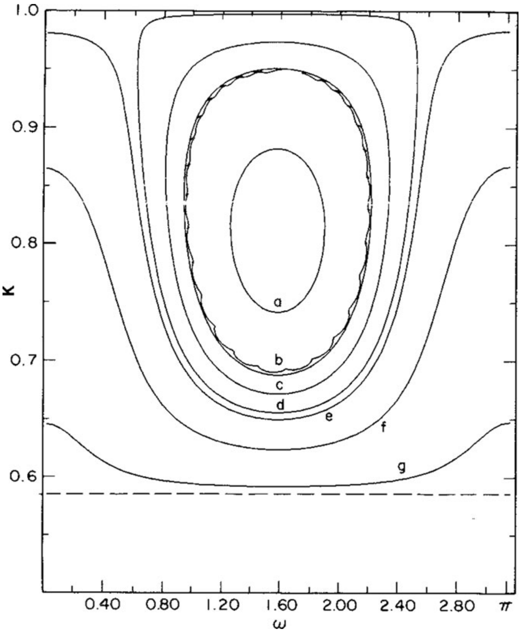

Figure 3. A family of trajectories in the $(g - K)$ space with $K = G/L$ for $|H|/L = 0.585$. From Heisler & Tremaine (1986).

The main characteristics of this model are: *(i)* the semi-major axis of the comet and the third component of the angular momentum are constant, *(ii)* the motion of the perihelion is strictly periodic with a period minored by $(4\sqrt{5\mu a^3}\rho_\odot)^{-1}$; *(iii)* from Eq. 3.2 the efficiency of the Galactic tides to reduce the angular momentum over one orbital period is at its maximum for $g = \pi/4 \bmod(\pi)$ and increases as $a^{7/2}$.

Some studies were also devoted to the quasi-integrable system where either the radial component is included or the averaging of the equations of motion is not performed (Brasser 2001; Breiter *et al.* 2008). It was also pointed out that the radial component of the tide should be included precisely because it breaks the integrability of the system (Matese & Whitmire 1996; Fouchard 2004).

It turned out that the tide is twice as efficient as the passing stars in injecting comets into the loss-cone (Torbett 1986; Heisler & Tremaine 1986; Bailey 1986). In addition, Duncan *et al.* (1987) have shown that the characteristic timescale for changing the perihelion distance, whatever is the semi major axis, is shorter for the Galactic tides than for the stellar perturbations.

Ultimately, an observational confirmation of the action of the vertical Galactic tides was pointed out by Delsemme (1987), who studied the distribution of the galactic latitudes of perihelia of 152 known original orbits of comets and found that these new Oort Cloud comets present a double-peaked distribution that is a characteristic of the disk tide (see also Wiegert & Tremaine 1999 for a more recent discussion one the distributions of orbital parameters of long period comets). Consequently from that time, stellar perturbations have been neglected when cometary injection is concerned.

4. The synergy

It appears that a synergy is at work when both the Galactic tides and the passing stars are at work as shown in Rickman *et al.* (2008). Figure 4 (from Rickman *et al.* 2008) shows a histogram plot of the number of comets injected into the observable region (defined by heliocentric distance smaller than 5 AU) as a function of time from the beginning till the end of the simulation. Three histograms are shown together: the one in black corresponds to a model with only Galactic tides, and the grey one to a model including only stellar perturbations. Finally, the top, white histogram is for the combined model that includes both tides and stars.

At first glance, it is evident that, at least after the first Gyr, the flux induced by the combined model is more than the some of the flux obtained with only the Galactic tides and the flux obtained with only the stellar perturbations. At the very beginning an anti-synergy is observed: the sum of the separate fluxes is larger than the combined flux. This phenomenon was found by Matese & Lissauer (2002), whose calculations were limited to only 5 Myr, and as they explained, it is typical of a situation where both tides and stars individually are able to fill the loss cone to a high degree.

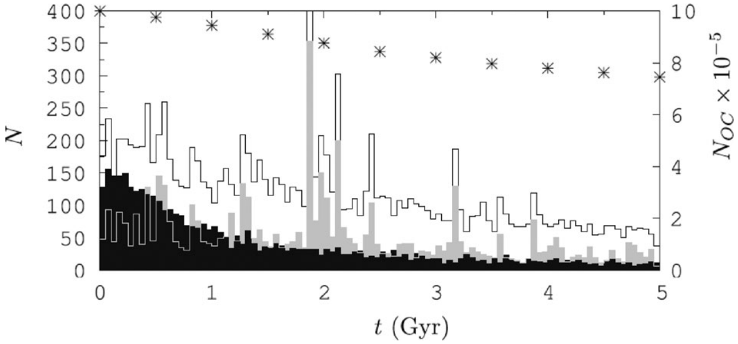

Figure 4. The upper diagram shows the number of comets entering the observable zone per 50 Myr versus time. The white histogram corresponds to the combined model, the black histogram to the Galactic tide alone, and the grey histogram to the passing stars alone. The asterisks indicate the number of comets remaining in our simulation for the combined model at every 500 Myr with scale bars to the right. From Rickman *et al.* (2008)

In order to quantify the synergy, Rickman *et al.* (2008) computed the filling factor f_{lc} of the loss cone for two different quasi quiescent periods, *i.e.* with no strong comets showers: one at the beginning and one at the end of the simulations. The filling factor

$\Delta(1/a)$	$f_{\rm lc}$ (Beginning)			$f_{\rm lc}$ (End)		
$(10^{-5}$ AU$^{-1})$	Tidal	Stellar	Combined	Tidal	Stellar	Combined
$(2-3)$	36%	10%	62%	0.6%	10%	52%
$(3-4)$	6.5%	1.1%	18%	–	2.3%	13%
$(4-5)$	0.09%	0.3%	2.2%	–	0.5%	2.0%
$(5-10)$	–	0.1%	0.15%	–	0.06%	0.11%
>10	–	0.0006%	0.0009%	–	0.0008%	0.0016%

Table 1. Filling factors for the observable part of the loss cone, computed for different ranges of semi-major axis and separately for the three dynamical models (tides-only, stars-only, and combined). From Rickman *et al.* (2008)

was computed for different ranges of orbital energy. Tab. 1 reproduces a selection of the results of Rickman *et al.* (2008).

The values of $f_{\rm lc}$ in the combined model are much larger than the sum of the two other entries, especially when $a > 25\,000$ AU even if a synergy is also at work in the inner Oort cloud. The loss cone was completely filled for smaller values of semi-major axis in Heilser (1990). This is likely due to lower value for the Galactic mid-plane density and somewhat higher stellar velocities used in Rickman *et al.* (2008).

The most important synergy mechanism of the Galactic tide and stellar perturbations is that the latter are able to repopulate the critical phase space trajectories that in the quasi-regular dynamics imposed by the tide lead into the loss cone (Dybczyński 2002; Fernández 2005). But note in Fig. 4 that the initial flux of the model with tides only is not matched by the white areas in the later part of the simulation. Thus, even though there is an ongoing replenishment of the tidal infeed trajectories due to the randomising effect of stellar encounters, this replenishment is not complete. Further experiments, not published yet, show that the massive stars have a key role in this replenishment.

The extension of the synergy to energy range where the tides are not able to inject comets into the observable region is rather explained by a 'constructive interference' mechanism for which the stellar perturbations is added to the tidal one.

Considering the distributions of orbital energy and direction of perihelions of the injected comets during the last quiescent period for the three models (see Fig. 5) Rickman *et al.* (2008) showed that: *(i)* the tide at the end of the integration is able to inject only few comets from the outermost part of the Oort cloud due to the non-integrable part of the tide, and the distribution of perihelion is typical of the tides imprint; *(ii)* the passing stars alone are poorly efficient to inject comets but the range of orbital energy extends to smaller semi-major axis, and the distribution of perihelion is nearly isotropic, *(iii)* the combined model yields a distribution of orbital energy as wide as for the stellar perturbations alone, with an increase on the number of comets per energy range consistent with the values of $f_{\rm lc}$ given in Tab. 1, and a perihelion direction distributions which carries, to some extend, the imprint of the tides.

Rickman *et al.* (2008) showed that this imprint might be even observed during a moderate comets shower. Consequently, one cannot rely on the perihelion distribution of the observable comets to determine whether or not we are in a comets shower.

5. Conclusion

The Galactical environment of the Sun affects the injection flux of comets from the Oort cloud under the influence of three main perturbers: *(i)* the passing stars, *(ii)* the giant molecular clouds, and *(iii)* the Galactic tides. The perturbations due to passing stars and tide are now well understood with a strong synergy between the two effects.

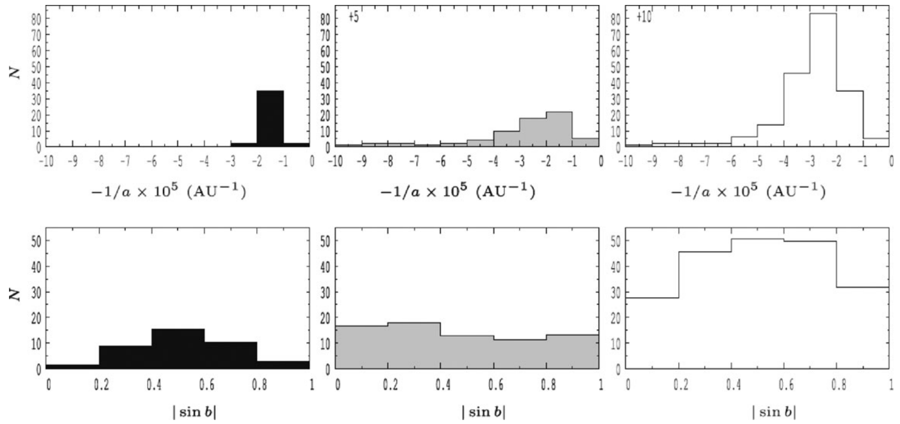

Figure 5. Distributions of $-1/a$, where a is the semi-major axis (top panels) and $|\sin b|$, where b is the Galactic latitude of perihelion (bottom panels), for the comets entering the observable region during 170 Myr near the end of the simulation. When present, numbers in the top-left corners of $-1/a$ distribution panels correspond to comets with $-1/a < -1 \times 10^{-4}$ AU^{-1}. The left column corresponds to the model with Galactic tide alone, the middle column to passing stars alone, and the right column to the model with both effects. From Rickman *et al.* (2008)

The modelling of the giant molecular clouds is still a gap in the long term study of Oort cloud comets dynamics, most of all because their effects are supposed to be destructive.

As regards the stellar and tidal effects, new improvements will be made after spatial mission as GAIA, which will give us a much better picture of the Galactical environment of the Solar System, and of the Solar motion within the Galaxy. Indeed, such motion should induce a variation of both the tidal strength and of the stellar population in the neighbourhood of the Sun.

Any realistic simulations of the cometary flux from the Oort cloud should include the planetary perturbations in a more realistic way than the loss cone technic. These perturbations were not considered in this review. The main difference will be that a dynamical path through the planetary region outside or near the Jupiter-Saturn barrier is allowed, and might even be quite common according to Kaib & Quinn (2009).

The problem of the cometary flux from the Oort cloud is related to the formation of the Solar System. This was out of the scope of the present review, however, it is still an open problem to built an Oort cloud consistent with both the actual flux of long period comets and the existence of objects as Sedna on one hand, and with the actual mass of the Kuiper belt (Charnoz & Morbidelli 2007). Many studies are devoted to this problem of the Oort cloud formation, the reader is referred to, *e.g.,* Brasser *et al.* (2006, 2007), Emel'yanenko *et al.* (2007), Kaib & Quinn (2008), Brasser (2008) among others, to have an idea on the state of art of this topic.

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