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A two-stage formation process for the Oort comet cloud and its implications
(Research Note)

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ABSTRACT

Aims. The aim is to check whether the *Nice* model – which refers to an initially compact configuration of the giant planets that lasted for about 700 Myr and eventually became unstable when Jupiter and Saturn crossed their 2:1 mean motion resonance – is consistent with what we know of the Oort cloud, and to provide an explanation for the mass and structure of the Oort cloud.

Methods. A two-stage formation scenario of the Oort cloud is proposed. The starting condition is the *Nice* model of planet migration, which contains a disc outside Neptune with a mass of 35 $M_\oplus$. From the formation efficiency I calculate the amount of mass deposited in the outer Oort cloud (comets with semi-major axis $a > 20\,000$ AU; the inner Oort cloud has comets with semi-major axis $a < 20\,000$ AU) and the innermost Oort cloud ($a \lesssim 3000$ AU). The latter formed when the Sun was part of its birth cluster i.e. before the outer cloud.

Results. The mass of the innermost Oort cloud directly inferred from the *Nice* model is 2.4 $M_\oplus$ to 7.2 $M_\oplus$, with a value around 5 $M_\oplus$ the most probable. The mass in the outer Oort cloud ranges from 0.5 $M_\oplus$ to 1 $M_\oplus$, with a value close to 0.9 $M_\oplus$ being the most likely. Current estimates of the mass in the outer cloud based on observations range from 0.6 $M_\oplus$ to 1.4 $M_\oplus$, in excellent agreement with predictions. Comets in the outer cloud come both directly from the disc outside Neptune as well as diffusion from the inner(most) cloud due to perturbations by passing stars.

Key words. comets: general – Oort cloud – solar system: formation

1. Introduction

Ever since Oort (1950) published his results on the orbital energy distribution of long-period and new comets nearly sixty years ago, astronomers have studied the formation and evolution of this quasi-spherical cloud of comets surrounding the Sun. Some of the earlier work includes that of Hills (1981) who demonstrated that comets coming directly from the postulated comet cloud (called the "Oort cloud") tend to have their semi-major axes larger than approximately 20 000 AU, beyond which the Galactic tide can torque their pericentre past Jupiter and Saturn in one orbit. For comets with smaller orbits, their visibility is greatly diminished since they cannot cross this Jupiter-Saturn barrier, and only become visible during comet showers (Hills 1981). As such, the term "inner" Oort cloud is usually reserved for comets residing in the cloud with semi-major axes $a < 20\,000$ AU (which are invisible unless there is a comet shower) while the term "outer" Oort cloud refers to comets with semi-major axes $a > 20\,000$ AU (and who can become visible during quiet periods). In addition, I shall use the term "innermost" Oort cloud for that portion of the cloud in which (90 377) Sedna resides, and is defined loosely for comets with $a \lesssim 3000$ AU; I shall argue here that this portion of the cloud formed much earlier than the rest.

A lot of work has been done to study the formation and evolution of the Oort cloud and to determine the amount of mass it contains. Dones et al. (2004) used the model of Levison et al. (2001) to simulate the formation of the Oort cloud in the current Galactic environment starting with test particles on nearly-circular, nearly-planar orbits in the vicinity of the giant planets. After 4 Gyr their results showed that only 2.5% of comets ended up in the outer cloud, down from about 5% around 1 Gyr. The overall efficiency of depositing material in the cloud after 4 Gyr is about 5% (down from 7.5% at 1 Gyr), with roughly equal mass in the inner and outer clouds. While the results were very interesting, the Dones et al. model had two shortcomings: it left too much material in the Scattered Disk (Duncan & Levison 1997) and could not explain the existence of the object (90 377) Sedna. Its discovery led Brasser et al. (2006, 2007) to study the formation of the Oort cloud while the Sun was still in its putative embedded cluster. They confirmed earlier studies that (90 377) Sedna's orbit could be reproduced in a dense enough environment less than a few million years. Unfortunately, there was no method available to determine how much mass is in said innermost cloud, apart from the estimate of 5 $M_\oplus$ by Brown et al. (2004) based on just one object. An unfortunate byproduct of the Brasser et al. (2006, 2007) model was that these innermost Oort clouds reproducing (90 377) Sedna did not extend farther than 10 000 AU from the Sun, so that the currently observed outer Oort cloud could not be reproduced. In addition,

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small objects cannot leave the planetary system if gas drag is present, so that the innermost cloud, where (90 377) Sedna resides, might be depleted of small objects. Brasser et al. (2008) performed numerical simulations trying to expand the inner Oort cloud from Brasser et al. (2006) with the aid of passing stars from the Galaxy, but the perturbations are generally too weak to significantly expand the cloud if it is closer than about 5000 AU to the Sun. Hence only a small percentage of comets from the inner and innermost cloud end up in the outer cloud.

Kaib & Quinn (2008) have performed similar simulations to those of Brasser et al. (2006) and Brasser et al. (2008) and report only 1% of their comets winding up in the outer Oort cloud after 4.5 Gyr, which is much lower than Dones et al. (2004). In addition, they concluded that the inner Oort cloud, especially comets with $a \lesssim 5000$ AU, are virtually unaffected by passing Galactic field stars. While one can argue that their simulations form the Oort cloud in two stages, their initial conditions are similar to those of Dones et al. (2004), so that the Oort cloud of Kaib & Quinn (2008) is forming (and eroding) on a continuous basis and not in two separate events as I will argue in this paper.

Here is where we stand today: the orbit of (90 377) Sedna supports the argument of the solar system being formed in a star cluster with some non-negligible density (e.g. Morbidelli & Levison 2004; Kenyon & Bromley 2004; Brasser et al. 2006). In such a cluster, the outer cloud would not form because not enough objects are implanted at such large distances (Brasser et al. 2006) and there is not enough late transfer from the innermost to the outer Oort cloud. In addition, kilometre-sized bodies should have been circularised by gas drag (Brasser et al. 2007) so that the innermost cloud that formed during the cluster stage should be depleted of small objects. Hence we need a late formation of the outer cloud i.e. once the solar system has left the natal cluster. The timescale of the late heavy bombardment (LHB) (Gomes et al. 2005) suggests that this event is related to the formation of the outer cloud. Therefore it follows that the origin of the LHB involved an outer disc of planetesimals, more or less in the lines of the *Nice* model (Tsiganis et al. 2005). I wish to explore the latter in this paper and will use the *Nice* model and results of Oort cloud formation studies to calculate the mass in the innermost and outer Oort clouds and compare it with estimates of the mass of the outer cloud.

The outline for this paper is as follows: in Sect. 2 I discuss the two-stage hypothesis and calculate the mass of the innermost and outer clouds based on the *Nice* model and previously-known formation efficiencies. In Sect. 3 I compare the mass obtained for the outer cloud with observations. In Sect. 4 I draw my conclusions.

2. Delayed formation of the outer Oort cloud

In 2005, Gomes et al. (2005) reported a scenario that could explain the late leavy bombardment (LHB) of the terrestrial planets. In their model – conveniently dubbed the *Nice* model after the southern French city where it was invented – the giant planets formed closer together than they are today, with Jupiter and Saturn being nearer to each other than their 2:1 mean-motion commensurability. The model contains a disc of material outside of Neptune extending to about 35 AU. The semi-major axes of the giant planets Jupiter, Saturn, Uranus and Neptune were 5.4, 8.2, 11.5 and 14.2 AU respectively (although Desch 2008, swaps Uranus and Neptune; see below). Slow leakage of material from the disc caused the giant planets to migrate and increased the separation between Jupiter and Saturn. Once these two planets crossed their 2:1 resonance, after approximately 0.5−1 Gyr, the system became unstable and Uranus and Neptune were scattered into the disc, which caused their orbits to circularise and migrate outwards. Eventually Neptune reached the edge of the disc around 30 AU and pushed out some of the material to form the Kuiper Belt. From this scenario it was found that the disc beyond the primordial Neptune contains 35 $M_\oplus$ in solids. This model explains many properties of the current Solar System. For want of better models, I shall use it as the source for the formation of the outer Oort cloud. The reader should be made aware that during the early stages of the Solar System's history, comets in the vicinity of Jupiter and Saturn that are larger than about 20 km in size end up in the innermost Oort cloud (Brasser et al. 2006, 2007). Smaller objects may not be able to escape the system because of aerodynamic drag experienced from the solar nebula. The simulations from Brasser et al. (2006, 2007) showed that unless the cluster had a central density $\rho_0 \lesssim 1000\ M_\odot$ pc^{-3}, no objects landed in what is now the outer cloud because both the tidal radius around the Sun is too small and the action of the cluster stars quickly emptied this region of comets. In addition, clusters which generated (90 377) Sedna did not produce comets in the outer cloud.

Hence the two-stage formation scenario has been set: the first stage is the building of the innermost cloud while the Sun was in its birth cluster according to the models of Brasser et al. (2006, 2007) or, if the Sun resided in an open cluster, according to the model of Kaib & Quinn (2008); (90 377) Sedna is a member of the innermost cloud. The second stage is initiated about 1 Gyr after the first when Jupiter and Saturn pass their 2:1 resonance and the material in the disc residing outside the initial system becomes available for building the second cloud, which is likely to proceed along the model of Dones et al. (2004). The outer cloud is formed during the second stage. This two-stage scenario can both explain the existence of (90 377) Sedna and generate an outer cloud that is not completely formed by the expansion of the innermost cloud through the action of passing stars or other perturbing bodies. The question now is whether this hypothesis is consistent with the mass estimates of the outer cloud using the primordial disc outside Neptune as a benchmark. The next subsections discuss this.

2.1. The mass of the primordial solar nebula

From studying the migration of Neptune, Gomes et al. (2005) concluded there was 35 $M_\oplus$ in solids between 15.5 AU and 34 AU; I shall use 16 AU and 36 AU since it mostly avoids using irrational numbers in what follows. The mass of the disc is computed from

$$M = 2\pi\Sigma_0 \int_{r_0}^{r_1} r^{1-\alpha}\,\mathrm{d}r = \frac{2\pi\Sigma_0}{2-\alpha}(r_1^{2-\alpha} - r_0^{2-\alpha}). \tag{1}$$

For the standard minimum-mass Hayashi disc (Hayashi 1981), $\alpha = 3/2$ and inserting it into Eq. (1) yields $8\pi\Sigma_0 = 35\ M_\oplus$, from which it follows that there is also 35 $M_\oplus$ between 4 AU and 16 AU and just 18 $M_\oplus$ between 4 AU and 9 AU; barely enough to form the cores of Jupiter and Saturn. Therefore, it is natural to wonder if the surface density profile was steeper than that suggested by Hayashi (1981). The Gomes et al. (2005) study only gave an estimate of the mass between 15 AU and 35 AU, but not between 5 AU and 15 AU. The mass between 4 AU and 9 AU, as well as 4 AU and 16 AU is listed in Table 1 for various values of the index if the surface density $\Sigma = \Sigma_0\, r^{-\alpha}$, taking the mass between 16 AU and 36 AU as 35 $M_\oplus$. The total mass in solids of

Table 1. Mass in solids between certain distances from the Sun as a function of the steepness of the surface density.

α	Mass 4−9 [$M_\oplus$]	Mass 4−16 [$M_\oplus$]
3/2	18	35
2	35	60
5/2	70	105
2.17	48.3	78.8

the minimum-mass solar nebula is about 40 $M_\oplus$ (e.g. Dones et al. 2004), and planet formation theories suggest that at least three to five times the minimum mass is needed to adequately form the cores of the giant planets (e.g. Thommes et al. 2003). The model with $\alpha = 2$ yields a total mass of 2.4 times the minimum mass while the model with $\alpha = 5/2$ yields 3.5 times the minimum mass. Kuchner (2004) argues that for extrasolar systems $\alpha = 2.0 \pm 0.5$, so the above results are within range. I performed the same experiment as Kuchner (2004) using known extrasolar systems as of June 2008 with three or more planets and obtained $\alpha = 1.95 \pm 0.21$. Desch (2008) computes the surface density for the *Nice* model and finds that $\Sigma = 12.8(r/1\ \mathrm{AU})^{-2.17}\ M_\oplus\ \mathrm{AU}^{-2}$, which is the last entry in Table 1.

Now that I have an estimate for the mass of the disc upon which the *Nice* model is built, I can use the results of Brasser et al. (2006) and Kaib & Quinn (2008) to estimate the mass in the innermost Oort cloud. This is done in the next subsection.

2.2. The mass of the innermost Oort cloud

Using the value for the mass obtained for the Jupiter-Saturn region (defined here as the region between 4 AU and 9 AU) from the previous section and taking a maximum efficiency of 15% from Brasser et al. (2006), the innermost cloud should have an upper mass value of 7.2 $M_\oplus$ while taking a minimum efficiency of 5% yields a mass of 2.4 $M_\oplus$. Therefore, the latter two values are the two extremes. With a more typical efficiency of 10%, the mass in the innermost cloud becomes 4.8 $M_\oplus$.

2.3. Mass of the outer Oort cloud

Following the calculations presented above, between 0.15 $M_\oplus$ and 0.43 $M_\oplus$ should be deposited in the outer cloud by expansion of the innermost cloud over about 4 Gyr through the peturbations of passing stars. In addition, the giant planets deposit some of the material from the disc outside Neptune in the outer cloud. Kaib & Quinn (2008) find that after 4.5 Gyr only 1% of the comets land in the outer cloud, down from 1.6% at 3.5 Gyr. These values are averaged over several simulations and have errors less than 0.5%. However, Dones et al. (2004) quotes that after 4 Gyr 2.5% of all the comets from the planetary region end up in the outer cloud. On the other hand, for dynamically warmer conditions, Dones reports a result of 1.7% after 4 Gyr, much closer to the results of Kaib & Quinn (2008) than the previous value of 2.5%, suggesting the latter result might be an anomaly; though I can only speculate its cause is less intrusive stellar encounters than for other simulations. Since this paper takes the LHB scenario (Gomes et al. 2005) into account, Oort cloud formation is delayed by about 0.5−1 Gyr so I shall use an intermediate efficiency of 1.4%. This is also in fair agreement with one of Dones' (Dones et al. 2004) results. Using this 1.4% as a guidance, I obtain that the outer cloud should contain 0.5 $M_\oplus$ of the 35 $M_\oplus$ that is available. If this percentage is just 1%, the mass is 0.35 $M_\oplus$ while an efficiency of 1.6% yields 0.56 $M_\oplus$. However, there will be some diffusion of comets from the innermost cloud that augment the mass of the outer cloud, so this phenomenon should be taken into account.

From Brasser et al. (2008), it was found that the percentage fraction of comets from the innermost cloud landing in the outer cloud after 4.5 Gyr as a function of the central density of the cluster the innermost cloud formed in, is

$$p = 35\left(\frac{\rho_0}{100\ M_\odot\ \mathrm{pc}^{-3}}\right)^{-0.53}\%. \tag{2}$$

From Brasser et al. (2006), the approximate relation between median distance and central density is

$$r_m = 10\,000\left(\frac{\rho_0}{100\ M_\odot\ \mathrm{pc}^{-3}}\right)^{-1/2}\ \mathrm{AU} \tag{3}$$

so that

$$p = 35\left(\frac{r_m}{10^4\ \mathrm{AU}}\right)^{1.06}\%. \tag{4}$$

In order to both retain (90 377) Sedna and deposit as much mass into the outer cloud as possible, it is required that (90 377) Sedna is on the inner edge of the innermost Oort cloud. Since Sedna's inclination is small and the closest part of the innermost Oort cloud appears to be flattened (Brasser et al. 2006; Kaib & Quinn 2008), this might seem like a plausible scenario. The necessary central cluster density in the model of Brasser et al. (2006) for (90 377) Sedna to be at the closest edge is about $10^4\ M_\odot\ \mathrm{pc}^{-3}$. The open cluster model of Kaib & Quinn (2008) requires an original stellar number density of 30 pc^{-3} to achieve the same result. With (90 377) Sedna on the inner edge, the median semi-major axis of comets in the innermost cloud is about 1500 AU, giving a median distance around 1900 AU for a cloud in virial equilibrium ($\langle e\rangle = 0.71$). For these parameters the percentage of comets landing in the outer cloud is about 6% and clearly the less dense the cluster, the easier it is to transport comets to the outer cloud. Therefore, any mass deposited directly into the outer Oort cloud by the *Nice* model should be augmented by 0.43 $M_\oplus$ if the innermost cloud has a mass of 7.2 $M_\oplus$, 0.29 $M_\oplus$ if the innermost cloud contains 4.8 $M_\oplus$ or 0.15 $M_\oplus$ if the mass of the innermost cloud is only 2.4 $M_\oplus$. Therefore, the mass of the outer cloud is in the range 0.5 $M_\oplus$ to 1 $M_\oplus$, with a value close to 0.9 $M_\oplus$ the most likely. The reader might wonder about replenishment from the second inner cloud i.e. the one formed by Uranus and Neptune in the simulations of Dones et al. (2004) and Kaib & Quinn (2008). However, this effect, as well as possible replenishment from the Scattered Disk (Fernández et al. 2004), is implicitly taken into account in the 1.4% figure quoted above.

All that remains now is to determine the mass deposited in the outer cloud by the *Nice* model during the second stage, as well as by the expansion of the innermost cloud through passing stars, and determine whether the sum is consistent with observations. This is explored in the next subsection.

3. Comparison with observations

One of the first estimates of the mass in the Oort cloud dates back to Weissman (1983) who used the observed distribution of cometary magnitudes corrected for observational selection effects by Everhart (1967) and a cloud population from Weissman (1982) to arrive at a mass of about 2 $M_\oplus$ for the whole cloud, which results in a mass between 55 $M_\oplus$ and 200 $M_\oplus$ in the Uranus-Neptune zone of our Solar System. The former number has frequently been updated (for a recent review see

Duncan et al. 2008). The largest uncertainties stem from three parameters: the uncertainties in mass-absolute magnitude relation, the average density of the nucleus of a comet and the total number of comets in the outer cloud. I will examine each of these in more detail.

The relation between the mass of a comet, m_c, its bulk density and its absolute magnitude H_{10} is of the form (Hughes 1988)

$$\log m_c = \log \rho_c + b_1 + b_2 H_{10}. \quad (5)$$

The value of $\log \rho_c + b_1$ ranges from 16.4 to 17.6 if the mass is in kilogrammes, with a value close to 17 as more common, while b_2 ranges from −0.4 to −0.6 (Whipple 1976; Hughes 1985; Bailey & Stagg 1988; Weissman 1996). The value −0.6 arises if the outgassing of material is evenly spread over the surface (Hughes 1988), which is not always the case (e.g. Hughes 2006), so the higher-end values are preferred. Data from comet 9P/Tempel 1 suggests that $b_1 + \log \rho_c = 19.1$ if $b_2 = -0.6$ (Hughes 2006). From Hughes (2006), again using 9P/Tempel 1 as a calibration, the relation between the radius in kilometres and the absolute magnitude is $\log r_c = 2.37 - 0.2H_{10}$.

Regarding the typical density of the nucleus, a common value of $\rho_c = 600$ kg m^{-3} has been used, based on comet 1P/Halley (e.g. Weissman 1996), but from a sample of Jupiter-family comets, a more typical value appears to be $\rho_c = 200$ kg m^{-3} (Weissman & Lowry 2006). From the Deep Impact mission on 9P/Tempel 1, its density has been determined as $\rho_c = 400 \pm 250$ kg m^{-3} (Richardson et al. 2007; Davidsson et al. 2007), again significantly lower than that based on 1P/Halley.

The number of comets in the cloud have so far relied on mass-absolute magnitude relations and measurements of the number of dynamically new comets passing close to the Earth. Weissman (1996) stated the number of comets in the outer cloud as $N_{\rm OOC} = 10^{12}$. Fairly recently Francis (2005) has used data from the LINEAR survey to revise the flux of Long-Period comets (LPCs) and states that said flux is about five times lower than that used by Weissman (1996), so that the revised number of comets in the outer cloud is $N_{\rm OOC} = 2 \times 10^{11}$, assuming all remaining parameters are the same as Weissman (1996). Emel'yanenko et al. (2007) independently published an estimate on the number of comets in the cloud based on numerical simulations and used the mass-absolute magnitude relation of Bailey & Stagg (1988) and derived that $N_{\rm OOC} = 2 \times 10^{11}$. Emel'yanenko et al. (2007) do say that this value might need to be reduced by a factor of 1.4, yielding $N_{\rm OOC} = 1.4 \times 10^{11}$ comets. The question now is can all of the above be tied together and yield a reasonable mass for the outer cloud?

Weissman (1996) quotes a number of 7 $M_\oplus$ under the assumptions that the number of comets in the outer cloud $N_{\rm OOC} = 10^{12}$ comets, the diameter of the comet with absolute magnitude $H_{10} = 11$ is $d_{11} = 2.3$ km and a typical cometary bulk density of $\rho_c = 600$ kg m^{-3} based on comet 1P/Halley, so that the mass $m_{11} = 4 \times 10^{12}$ kg. Additional assumptions are that LPCs have a shallow size distribution (Everhart 1967), with index 2 for the cumulative distribution up to a size $d_{\rm crit} \sim 20$ km, and follow a steep distribution at larger sizes. For these assumptions, most of the mass in the Oort cloud is in bodies with diameters between d_{11} and $d_{\rm crit}$, and the average mass of a comet $\bar{m}_c$ is of the order $d_{\rm crit}/d_{11} \times m_{11}$, or $\bar{m}_c \sim 4 \times 10^{13}$ kg, giving a mass for the outer cloud of $N_{\rm OOC}\, \bar{m}_c = 4 \times 10^{25}$ kg i.e. 7 $M_\oplus$. Using 9P/Tempel 1 as a calibration, I find that $m_{11} = 4 \times 10^{12}$ kg too, similar to Weissman (1996). In order to estimate the mass of the cloud in a manner similar to Weissman (1996), I have to validate his assumption about the size distribution being much steeper than cumulative index 2 for $d_{\rm crit} \gtrsim 20$ km. Weissman & Levison (1997) found a differential size distribution index $q = 4.5$ for objects larger than 10 km and $q = 3$ for smaller objects. Fraser et al. (2008) find $q = 4.25$ for the Kuiper Belt down to objects with diameters about 50 km in size and numerical simulations in the region by Kenyon & Bromley (2001) support this idea and a break around 2−20 km. Weissman & Lowry (2006) find a cumulative index of $\alpha = 1.73$ (hence the differential index $q = 2.73$) for Jupiter-family comets in the range 1.4 km to 6 km, supporting the shallow-size distribution scenario. However, the most compelling result is from Morbidelli et al. (2008) who examined the absolute magitude (H) distributions of the cold and hot populations in the Kuiper belt and of the Trojans of Jupiter and evidence that the Trojans have been captured from the outer part of the primordial trans-Neptunian planetesimal disc. They develop a sketch model of the H-distributions and confirm it is consistent with the *Nice* model. They find a break in the distribution at diameter $d_{\rm crit} = 100$ km, with a cumulative size distribution index of 5.4 for larger objects and 2 for smaller objects.

Therefore, setting the break at about 20 km as Weissman (1996) did is probably acceptable, and with the updated number of comets in the cloud, I arrive at an outer cloud mass of 1.4 $M_\oplus$, though it could be as low as 1 $M_\oplus$ if the number of comets need to be reduced as stated by Emel'yanenko et al. (2007). Using the Bailey & Stagg (1988) relationships between absolute magnitude and mass and radius of the comet, I get $m_{11} = 2.5 \times 10^{11}$ kg and $d_{11} = 1.1$ km, yielding an outer cloud mass of 0.2 $M_\oplus$, which seems very low. By using the data from Morbidelli et al. (2008), I get $N_{\rm OOC}\, \bar{m}_c = 5.24 \times 10^{24}$ kg i.e. 0.87 $M_\oplus$. However, the data from Morbidelli et al. (2008) shows there are 10^{12} comets with diameters larger than 1 km, and if only 1.4% of those end up in the outer cloud, we have only $\sim 10^{10}$ comets in the outer cloud, an order of magnitude lower than previously thought. This issue will be addressed in another publication.

Duncan et al. (2008) argued that if one assumes that the outer cloud's mass contains very few comets with $H_{10} < 3$, which is the brightest comet seen thus far by LINEAR (Francis 2005), the mass of the outer cloud becomes as much as 3 $M_\oplus$ using the absolute magnitude-mass relation of Weissman (1996) or as little as 0.6 $M_\oplus$ if the Bailey & Stagg (1988) relation is used. Lower-end values seem to be more consistent with current models of the dynamical evolution of the outer Solar System (Duncan et al. 2008). In addition, the work of Rickman et al. (2008) hints to a somewhat higher transfer efficiency from the Oort cloud to the LPC population, so the above estimates might be reduced somewhat (say by a factor of 1.2).

Summarising all of the above, I now have an approximate window of 0.6−1.4 $M_\oplus$ for the mass of the outer cloud from observations. From the previous section, I computed a mass between 0.5 $M_\oplus$ and 1 $M_\oplus$, in very good agreement with observational estimates!

4. Summary and conclusions

I have suggested a two-stage process for the formation of the Oort comet cloud, based on the *Nice* model of planet migration (Gomes et al. 2005). After the instability triggering the late heavy bombardment, the amount of material directly deposited in the outer Oort cloud is about 0.5 $M_\oplus$, on the lowest end of recent estimates of the mass of the outer cloud of 0.6−1.4 $M_\oplus$. Therefore, it is likely that something must replenish it. This replenishing reservoir could be the innermost Oort cloud and the primary mechanism is passing stars scattering the comets to the outer cloud. Using the mass in the primordial Jupiter-Saturn region inferred from the *Nice* model from Desch (2008) and the efficiencies found by Brasser et al. (2006, 2007), the mass of the first inner cloud ranges from 2.4 $M_{\oplus}$ to 7.2 $M_{\oplus}$, with a value around 5 $M_{\oplus}$ the most likely. Using (90 377) Sedna as an indicator for the inner edge of the innermost cloud yields a transport efficiency of about 5% to the outer cloud, so that the total mass of the outer cloud ranges from 0.5 $M_{\oplus}$ to 1 $M_{\oplus}$, with a value of 0.9 $M_{\oplus}$ the most likely. This result is consistent with current observations, but once again on the low end.

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