Outer Solar System Possibly Shaped by a Stellar Fly-by

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Abstract

The planets of our solar system formed from a gas-dust disk. However, there are some properties of the solar system that are peculiar in this context. First, the cumulative mass of all objects beyond Neptune (trans-Neptunian objects [TNOs]) is only a fraction of what one would expect. Second, unlike the planets themselves, the TNOs do not orbit on coplanar, circular orbits around the Sun, but move mostly on inclined, eccentric orbits and are distributed in a complex way. This implies that some process restructured the outer solar system after its formation. However, some of the TNOs, referred to as Sednoids, move outside the zone of influence of the planets. Thus, external forces must have played an important part in the restructuring of the outer solar system. The study presented here shows that a close fly-by of a neighboring star can simultaneously lead to the observed lower mass density outside 30 au and excite the TNOs onto eccentric, inclined orbits, including the family of Sednoids. In the past it was estimated that such close fly-bys are rare during the relevant development stage. However, our numerical simulations show that such a scenario is much more likely than previously anticipated. A fly-by also naturally explains the puzzling fact that Neptune has a higher mass than Uranus. Our simulations suggest that many additional Sednoids at high inclinations still await discovery, perhaps including bodies like the postulated planet X.

Key words: Kuiper belt: general – minor planets, asteroids: general – open clusters and associations: general – planetary systems – planets and satellites: formation – protoplanetary disks

1. Introduction

Explaining the shape of the solar system once seemed simple—the planets formed from a smooth disk surrounding the young Sun, orbiting in a plane on almost circular orbits. However, there are some features of the solar system that seem at odds with this picture. First, the surface density of the solar system drops by a factor of more than 1000 outside Neptune’s orbit at 30 au (Morbidelli et al. 2003). Second, most objects outside Neptune (trans-Neptunian objects [TNOs]) move on eccentric, inclined orbits ($i > 4^\circ$) relative to the planetary plane (Gladman et al. 2008). Third, such objects exist even outside the range of influence of the planets. All three points strongly indicate that the outer reaches of the solar system must have been considerably modified by some process(es) that took place after its formation.

First, we want to have a closer look at the objects that move on peculiar orbits despite being outside the range of influence of Neptune. They are referred to as Sedna-like objects or Sednoids, named after Sedna, which was the first observed object of this kind (Brown et al. 2004). When another object of this kind, namely, 2012 VP113, was discovered (Trujillo & Sheppard 2014), it became clear that a population of planetesimals exist that share similar orbital elements (see also de la Fuente Marcos & de la Fuente Marcos 2014). They are part of the outer regions of the solar system located between the Kuiper Belt and the Oort Cloud and orbit on extraordinary wide ($a > 150$ au), eccentric orbits with large perihelion distances, $q > 30$ au. All these objects have inclinations with respect to the ecliptic in the range of $i = 10^\circ–30^\circ$ and arguments of perihelion of $\omega = 340^\circ \pm 55^\circ$, so that a common origin has immediately been suggested (de la Fuente Marcos & de la Fuente Marcos 2014; Trujillo & Sheppard 2014). By now it is believed that about 20 Sednoids are known; they consist of those originally listed in Trujillo & Sheppard (2014) and de la Fuente Marcos & de la Fuente Marcos (2014), additional objects suggested in Sheppard & Trujillo (2016), and the recently discovered 2014 UZ224 (Gerdes et al. 2017).

At such large distances from the Sun, the Sednoids are outside the area of influence of even Neptune. However, it seems also that their aphelion distances are too short for them to be Oort Cloud objects (Brasser & Schwamb 2015). In principle, it would be possible that they were excited to these orbits owing to chaotic diffusion. However, this is also unlikely, because it would require a time span longer than the age of the solar system to obtain the distance of Sedna (Russman & Wisdom 1988). This means that an outside influence is likely responsible for their orbits. There have been several suggestions regarding what such an outside influence could be. One suggestion is that the Sednoids were captured from the outer disk of another star during a close fly-by (Kenyon & Bromley 2004; Morbidelli & Levison 2004; Jilková et al. 2015). Alternatively, the postulation of a possible wide-orbit ninth planet or planet X (Brown et al. 2004; Gomes et al. 2006; Soares & Gomes 2013; Batygin & Brown 2016) has gained renewed popularity recently.

Here we suggest a somewhat different process whereby the Sednoids would have been excited to their current orbits also as a result of the close fly-by of a star. However, in contrast to the capture scenario, here the Sednoids would originate from the Sun’s own, originally more extended disk. In Section 2 we test in how far one can obtain the different properties of the TNOs, namely, the Sednoids, the cutoff at 30–35 au, the Kuiper Belt population, and some additional outer solar system features. Afterward, we restrict the parameter space to fly-bys that match best all the outer solar system properties. This is done by performing an extensive parameter study of the effect of fly-bys on disks and applying the criteria that correspond to the observed properties to the obtained simulation results. We will
see that the beauty of this scenario lies in the fact that one can obtain all these features, and more, in one single event.

A new theory not only has to pass the test of reproducing the data and being fairly simply, which this model fulfills, but also show that such a process is likely to happen. Therefore, we perform simulations to determine the frequency of such close fly-bys in star clusters as the birth environment of the solar system. Here we model the different phases of star cluster development and make predictions for each of these phases in Section 3. We discuss the various options when such a fly-by could have happened during the past 4.65 Gyr since the formation of the Sun. In Section 4 the results are detailed and compared to other models for shaping the outer solar system.

2. Relevant Fly-by Parameter Space

2.1. Method

In a first step we determine the parameter space of fly-bys that leads to a cutoff at 30–35 au. We simulate the Sun as being surrounded by a disk of test particles. This disk could represent either a protoplanetary or a debris disk; the inner part may even contain the already-formed planets. Accordingly, we assume that the disk mass $m_{\text{disk}}$ is much smaller than the mass of the Sun, which is the case for most protoplanetary disks and all debris disks. Under these conditions, one can neglect viscosity and self-gravity between the disk particles, unless one is interested in the long-term behavior after the fly-by. Although the giant planets, in particular Neptune, in influence also the orbital parameters of the TNOs over 1 the billions of years, we do not include these forces explicitly in our simulations, because in this first proof-of-principle study we are mainly interested in the properties of distant TNOs, like Sedna, just after the fly-by. On these distant TNOs the influence of the planets is negligible (for more details see Section 2.2 and Equation (3) therein). In this case the problem reduces to a gravitational three-body interaction between the Sun, the perturber star, and each disk particle (Hall et al. 1996; Kobayashi & Ida 2001; Musielak & Quarles 2014).

Disks with an outer radius of 100, 150, or 200 au were modeled with the tracer particles initially orbiting the Sun on circular Keplerian orbits. An idealized thin disk (Pringle 1981) was assumed with all particles initially located on the same plane (but see exceptions in Section 2.2). In our parameter study we used 10,000 massless tracer particles to model this disk. This particle number is a compromise made to be able to scan the extensive parameter space while still resolving the relevant populations. For the problem considered here it is relevant to have a sufficiently high resolution in the outer part of the disk. This was achieved here by using an initially constant particle surface density and post-processing the data by assigning different masses to the particles to model the actual mass density distribution (Hall et al. 1996; de Juan Ovelar et al. 2012; Steinhausen et al. 2012). This is computationally much more efficient than increasing the particle number.

We modeled fly-bys with perturber masses of 0.3, 0.5, 1.0, 2.0, 5.0, 10, 20, and 50 $M_\odot$ at periastron distances of $r_{\text{peri}} = 30$, 50, 100, 120, 150, 200, 250, 300, 500, 700, and 1000 au. The parameter space in orbital inclination was covered in steps of $10^\circ$ and the angle of periastron in steps of $45^\circ$. The extent of our parameter study is summarized in Table 1, amounting in total to 5643 parameter combinations. It is assumed that the perturber moved on a parabolic orbit, which is a reasonable assumption as long as the star cluster is not extremely dense.

Table 1 Parameter Space of the Modeled Fly-bys

| Parameter | Simulated Values |
|-----------|------------------|
| Perturber mass | 0.1, 0.3, 0.5, 1.0, 2.0, 5.0, 10, 20, 50 |
| Periastron distance | 30, 50, 100, 120, 150, 200, 250, 300, 500, 700, 1000 |
| Inclination | 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170, 180 |

Note. The perturber mass is given in solar masses, the periastron distances in au, and the inclination and orientation in degrees.

2.2. Fly-by Processes Leading to Solar-system-like Features

First, we select a subset of simulations that yield a disk size in the range of 30–35 au. In the literature one often finds that the disk size is reduced to 0.3–0.5 times the periastron distance. However, this approximation holds only for the fly-by of a solar-mass star (Kobayashi & Ida 2001). In a cluster a wide variety of stars with masses ranging from 0.08 up to $\approx 100 M_\odot$ might in principle act as a perturber. However, not each perturber mass is equally likely. Actually fly-bys of stars with masses $\approx 0.5 M_\odot$ or stars with masses exceeding $5 M_\odot$ are the most common ones to lead to disk truncation (Olczak et al. 2010, 2012; Vincke & Pfalzner 2016).

A Runge–Kutta Cash–Karp scheme was used to determine the particle trajectories. The simulation starts and ends when it holds for all particles bound to the Sun that the force of the star flying by is less than 0.1% of that of the Sun. To obtain a statistically sound sample, we performed 20 simulations for each fly-by scenario with different random seeds for the initial particle distribution. At the end of the simulation properties such as eccentricity, inclination, periastron distance, semimajor axis, and orbit-averaged position are stored for each test particle. For a more detailed description of the numerical method see Bhandare et al. (2016). The resulting particle distributions are then compared to the observational data.
space given in Table 1, it functions as a first indicator to
determine the relevant subset of fly-bys. In the next step, we identify in this subset the fly-bys that lead simultaneously to a population that represents the Kuiper Belt reasonably well and produces Sednoids. Here one has to keep in mind that after the fly-by the objects in the inner Kuiper Belt region will be affected by interactions with Neptune for a considerable time afterward. We do not model this long-term behavior here. Therefore, it is not our aim to reproduce the inner Kuiper Belt structure as closely as possible. Instead, our prime goal is to obtain a good match for the Sedna-like objects, while having a reasonable fit for the Kuiper Belt.

Figure 1 illustrates fly-bys of perturbers of different mass ($M_2 = 0.5, 1, 5 M_\odot$) that lead to a mass density drop at 30–35 au distance from the Sun. The perihelion distance is always chosen in such a way as to lead to a 30–35 au disk. The top row indicates the eccentricity distribution of the matter with a central area of most particles on circular orbits and more eccentric orbits at larger distances from the Sun. The eccentricities are indicated by the different colors given in the bar. The origin of the different eccentricity populations in the original disk can be seen in the bottom row, where matter indicated in gray becomes unbound from the Sun. Note that in panel (c) the path of the perturber is not visible because it is outside the shown frame.

Despite the general similarity of the three sets of fly-by parameters, there are considerable differences in the location of the different regions and the relative portions of particles becoming unbound or having similar properties. In short, higher-mass stars lead to more compact configurations with very few objects beyond 60 au—considerably less than one finds in the solar system. We find that masses in the range $M_2 = 0.5–1 M_\odot$ usually correspond better to the Kuiper Belt population than fly-bys of higher-mass stars and are the only ones able to produce objects like Sedna.

However, it is not only the periastron distance and the perturber mass that influence the resulting population but also the relative orientation between the plane of the disk and that of the path of the perturber that are extremely important. In order to obtain a good fit with the inclinations of the TNOs, the fly-by has to be inclined and at a certain orientation. Going through the so-obtained subset, we look for those that give the best fit to all three properties—30 au drop-off, Kuiper Belt, and Sednoids. Of the parameter combinations listed in Table 1, a very good match to the observed properties is found for the fly-by of a star of mass $m_p = 0.5 M_\odot$ on an inclined orbit (60°) with an angle of periastron of 90° passing the Sun at 100 au, which was initially surrounded by a 150 au-sized disk. Figure 2(a) shows the distribution of particles after the fly-by similar to Breslau et al. 2017). It can be seen that the fate of the particles follows a complex pattern.
Figure 1(a), but this time on an inclined orbit as described above. This fly-by effectively truncates the disk, leaving the system inside 30 au basically undisturbed (Figure 2(a)) while depleting the total mass in the Kuiper Belt region to <1% of its initial mass. At the same time, it excites the trans-Neptunian belt and forms a family of Sednoids. Figure 2(b) illustrates the original positions of the particles color-coded with their final eccentricity after the fly-by. Here dark green corresponds to the possible sites of the origin of Sedna. During such a fly-by matter is not exclusively transported outward, but a considerable fraction also moves inward. The reason for this behavior is that not only super-Keplerian velocities but also sub-Keplerian velocities are induced by fly-bys (Pfalzner 2003; see Figure 2(c)).

The fact that the fly-by of a star with mass \(\approx 0.5 M_\odot\) gives a relatively good fit is in accordance with the above-mentioned result that the most common disks truncating fly-bys in a cluster are those with \(\approx 0.5 M_\odot\). During this fly-by, for all planets the induced eccentricities are even in extreme cases always <0.05, but they can be considerably lower, depending on the relative position of the planets at the moment of periastron passage of the perturber. Thus, the influence on the planetary orbits is negligible.

The fly-by parameters we obtain are very similar to the case Kobayashi et al. (2005) investigated for the formation of the Kuiper Belt population, where they modeled also the effect of a \(0.5 M_\odot\) perturber. However, they did not obtain the cold Kuiper Belt population or a Sedna-like object. Punzo et al. (2014) had a similar problem for different fly-by parameters. In both cases the reason is two prime differences in the setup, namely, we have a considerably higher resolution in the outer regions of the disk, and our initial disk is larger. Little as these differences seem, they have severe consequences. In smaller disks one obtains many of the other Sednoids, but not Sedna itself because its point of origin is most likely between 100 and 120 au. The absence of a population with low eccentricities (cold Kuiper Belt) in these simulations is because this population is considerably smaller than that of the hot Kuiper Belt. Thus, one requires a relatively high number of test particles in the disk outskirts, which is more difficult to achieve with a 1/r resolution in the test particle distribution.

Before discussing the different populations that can be seen in our simulations, we want to point out that although the above-given parameters lead to a relatively good fit, it is far from clear whether they are the optimal choice. Due to the extensive parameter space, our grid of simulations is necessarily still quite coarse. It is better to say that if a fly-by really shaped the outer solar system, then it would have been by a star in the mass range \(M = 0.3–1.0 M_\odot\), passing at a perihelion distance of between 50 and 150 au, with an inclination in the range of 50°–70° and an angle of periapha between 60° and 120°. The next steps would be to test with a finer grid in the relevant parameter space and calculate how the Kuiper Belt population would develop after a fly-by owing to the interactions with Neptune. Both tasks are beyond the scope of this work because (i) the latter would require a different type of code again and (ii) one would need still better observational constraints on the Kuiper Belt and Sednoid population to have a solid case to test for in an automated way.

Figure 3 shows the eccentricity versus inclination distribution after the fly-by with the above-selected properties. For comparison we included the four most extreme Sednoids in the plot. It can be seen that Sednoids would be a natural outcome of such a fly-by. To obtain a closer grip on where the Sednoids would have most likely resided before the fly-by, we look in Figure 3(b) at where particles with final semimajor axis equivalent to that of Sedna (red) and 2012 VP113 (green) originate from. It can be seen that, in principle, any location between 30 and 150 au would be possible, but that the likelihood of Sedna and 2012 VP113 originating from the area between 100 and 150 au is considerably higher. This explains also why neither Kobayashi et al. (2005) nor Punzo et al. (2014) found Sedna-like objects, as they modeled only populations reaching out to 100 and 90 au, respectively. We see in Figure 4(c) that in the eccentricity versus periapha plane also Sedna-like objects are clearly expected after such a fly-by. In summary, Sedna-like objects are a common outcome of fly-bys under the condition that the initial disk extended at least to 100–120 au.

Next, we present a detailed comparison of the TNO population expected from our simulations with the observed one. Figure 4 compares known TNOs to simulation particles. To ensure a fair and relevant comparison, we apply two criteria: (a) we plot only TNOs and simulation particles that are not strongly coupled to Neptune, and (b) we plot only simulation particles that would likely be detected from Earth.
First, we apply criterion (a) by selecting only TNOs with $a > 30$ au and $T_N > 3.05$. $T_N$ is the Tisserand parameter with respect to Neptune, given as

$$T_N = \frac{a_N}{a} + 2 \left(1 - e^2\right) \frac{a}{a_N} \cos(i),$$

where $a_N$ is Neptune’s semimajor axis and $a$, $e$, and $i$ are the semimajor axis, eccentricity, and inclination of the TNO, respectively. The Tisserand parameter is commonly used to distinguish asteroids from Jupiter-family comets in terms of their dynamics with respect to Jupiter: asteroids, with $T_J > 3.05$, are dynamically decoupled from Jupiter, whereas comets, with $T_J < 3$, have orbits that are strongly coupled to the gas giant (Jewitt et al. 2009). Analogously, we use $T_N > 3.05$ to select only those TNOs that are dynamically decoupled from Neptune. We apply similar dynamical criteria to the model particles.

Second, we impose the detectability threshold (b) to the model particles. TNO surveys have complicated detection biases, but the main and most general effect is that TNOs tend to be discovered when at perihelion (Shankman et al. 2017). To account for this, we select only simulation particles with perihelia less than $q = 80.4$ au, which is the value for 2012 VP_{113}, the TNO with the largest known perihelion (Trujillo & Sheppard 2014).

As already pointed out by Kobayashi et al. (2005) and Punzo et al. (2014), fly-bys can produce the excited orbits dominant in this region very well. This can be seen in Figure 4, where the simulation results are compared with the observed properties of the TNOs. Here the representation of the simulation results is different from those in the previous plots, as we assumed a $1/r$-dependence of the initial disk and weight accordingly. The particles in the plot are only those with a high mass density in this area. We chose this approach because this probably resembles the observational selection effects. However, our results indicate that this may be problematic for some features of the TNO population. We see in accordance with Kobayashi et al. (2005) and Punzo et al. (2014) that the overall properties of the hot Kuiper Belt are well reproduced.

However, their problem was that the cold Kuiper Belt population was missing; they had no particles with $e < 0.1$. We pointed out earlier that for the work by Kobayashi et al. (2005) this was most likely a resolution problem. If we look at our high-resolution plot (see Figure 3), we clearly see a population with the eccentricity all the way down to $e = 0$. This can be seen better in Figure 5, where we explicitly show only this population. (Note that this area has a relatively low mass density, which is why it is missing in Figure 4(a), where we show only areas of high mass density.) This confirms that one needs a sufficiently high resolution to obtain the cold Kuiper Belt population.

Going back to Figure 3(b), we can see where this low-eccentricity population originates from. All matter on fairly circular orbits is indicated in blue in this plot. Interestingly, we find several regions outside the central planet area where the particles still move on orbits with $e < 0.1$ after the fly-by, some of them at very large radial distances ($>100$ au). In addition, there is a small population scattered within the red area (0.1 < $e$ < 0.4). In our scenario the cold Kuiper Belt population would originate from this population plus the small blue area at 45–50 au. Basically, it is the population more or less at the opposite side of the periastron passage that remains fairly undisturbed. The relative size and location of this area depend strongly on the actual fly-by parameters. This
difference is highlighted when compared to the equivalent coplanar fly-by (Figure 1(a), bottom), where these areas (here in red) are at very different locations and much smaller. Therefore, it is no longer the question whether a fly-by gives also a cold Kuiper Belt population, but which fly-by parameters give the best match to the observed population.

Figure 3(a) also shows that there is an actual gap between the cold and hot population in inclinations similar to the observed one. However, for our scenario we find a slightly lower number of cold Kuiper Belt objects (5%–8% of the total Kuiper Belt population) compared to the observed ~10%. In addition, most objects are more inclined than in the observed population. The low number of cold Kuiper Belt objects and the higher inclination may be due to either the long-term evolution missing here or the model assumptions. Here we assumed an idealized thin disk that might not be realistic. If the disk had a nonzero scale height, the number of low-inclination objects among the cold Kuiper Belt population would probably be higher. Second, Punzo et al. (2014) showed that secular evolution quickly leads to “cooling” of the eccentricities and inclinations, making the population colder. The importance of both these effects will be investigated in follow-up studies.

Closer inspection reveals some additional features in Figure 4. Sheppard & Trujillo (2016) found a new family of TNOs that have relatively large periastra but low eccentricities. These are also present in our (so far) best-fit solution. We have indicated these objects in Figure 4 as blue asterisks. Actually, we would expect that similar objects but with even larger periastra (100–200 au) await detection.

We must admit that there is also one feature that we would expect from our simulations but has so far no equivalent in the observations. That is a population with large periastra (100–200 au) and large eccentricities (0.6–0.8) but low inclinations (5°–10°). We will have to check in the follow-up study whether this population always occurs in such fly-bys or is just a feature of the particular parameters we chose here.

Unlike the so-far-detected exoplanetary systems, where all planets of a system seem to be of fairly equal mass and separation, the separations of the giant planets in the solar system increase while their masses decrease steadily with distance to the Sun (Weiss et al. 2018). The mass distribution of the solar system planets is usually attributed as being a direct consequence of that in the disk from which they formed. There is only one exception: Neptune’s mass (17.2 M_\text{Earth}) is larger that that of Uranus (14.6 M_\text{Earth}). There have been several theories trying to explain this situation (Levison et al. 2008); however, a fly-by would also naturally explain this fact. We saw earlier that as a consequence of the fly-by most matter beyond Neptune’s orbit moves outward, but some portion also moves inward. This matter comes partly from very distant locations (50–150 au) and concentrates somewhere between 30 and 35 au (see Figure 6(a)). This matter transport creates a bump that is located at 35–60 au right after the fly-by. Afterward, it moves inward (Figure 2(c)), and the particles have final eccentricities of 0.0–0.4 (see Figure 2(c), bottom). The matter gets accreted every time the particles are at their

**Figure 4.** Resulting distribution of objects after the fly-by, for (a) inclination vs. semimajor axis, (b) eccentricity vs. semimajor axis, and (c) eccentricity vs. perihelion distance. The red symbols indicate the observed objects, and the black symbols indicate the predictions from the model.

**Figure 5.** Close-up of the cold Kuiper Belt population from Figure 3(a).
perihelion and approach closely Neptune’s orbit. With the entire matter contained in this “bump” corresponding to approximately 1–2 Earth masses, this is somewhat less than the 2.6 $M_{\text{Earth}}$ mass difference between Uranus and Neptune, but self-gravity effects or slightly different fly-by parameters could account for this difference. This will be tested in follow-up studies.

In summary, a fly-by with the parameters in the above-described range reproduces many of the features of the outer solar system all in one go. Thus, this model fulfills two demands on a new theory—it agrees largely with the available data, and it is simpler than existing models. The question now is, is it also likely that such an event happened? In the following section we want to address the question of how likely such a close fly-by event would have been during the past 4.56 Gyr.

3. Frequency of Solar-system-forming Fly-bys

Fly-bys are often regarded as quite rare events, but they happen even today; however, most of them are distant and mainly influence the outer Oort Cloud (Bailer-Jones 2018). Nevertheless, they provide a considerable amount of long-period comets (Dones et al. 2015; Feng & Bailer-Jones 2015; Mamajek et al. 2015; Feng et al. 2017). The closest recorded fly-by in recent times was that of WISE J072003.20-084651.2 (Scholz star), which passed approximately 70,000 yr ago at a distance of $\approx$52,000 au (Mamajek et al. 2015). Thus, it was 520 times more distant than the type of fly-by we are considering here. However, as the Sun formed like most stars in a cluster environment, the close fly-by frequency is generally assumed to have been considerably higher in its initial stages. Existing estimates of close fly-by frequencies are mostly based on the simulations of the fly-by rate in a cluster with a density distribution similar to the ONC (Proszkow & Adams 2009; Adams 2010). In contrast to the temporal evolution of the cluster modeled here, they investigate the case of a relatively constant average stellar density of 100 stars pc$^{-3}$. They find that the frequency of fly-bys at 90 au should occur with a rate of $10^{-4}$ to $10^{-2}$ Myr$^{-1}$ during the first 10 Myr. Their argument continues with the frequency value $10^{-3}$ Myr$^{-1}$, and they conclude that this is a low probability.

Given that 90% of the Milky Way clusters largely dissolve within 10 Myr (Lada & Lada 2003), it is often assumed that basically no close fly-bys happen afterward. This is the main reason why previous suggestions of fly-bys possibly being responsible for the properties of the outer solar system have not received much attention. It is often argued that in these outer areas objects where the TNOs are located, it would require well over 10 Myr to grow to their current size and that at that time fly-bys would be extremely rare. However, as already suggested by Davies et al. (2014), despite the fly-by frequency at later times being relatively low, even at such a low occurrence rate there was a realistic change for close fly-by given the long time span of 4.5 Gyr. They estimated that a close fly-by is approximately as likely to have happened during the first 10 Myr as during the consecutive 4.5 Gyr.

Here we want to have a renewed look at the frequency of close fly-bys for the following reasons:

1. Newly available high-resolution images of disks around stars younger than 10 Myr show prominent ring structures at several tens to hundreds of au. Many authors interpret these as signatures of already-formed or currently forming planets (Testi et al. 2015; Andrews et al. 2016; Fedele et al. 2018). If gas giants can form at such distances from their host star in such a short time span, it can no longer be excluded that TNO-sized objects could form on timescales $<$10 Myr. This means that the argument against an early fly-by ($<$10 Myr) has become weaker.

2. The estimate of the fly-by frequency made several simplifying assumptions. First, a cluster consists of a broad spectrum of stellar masses, so taking an equal-mass fly-by as an example might not be representative. Second, the cluster was assumed to be in a quasi-steady state, meaning that the stellar density remained approximately constant over the simulation time. However, clusters are
highly dynamical systems, so it might be essential to determine the fly-by frequency during all phases of the cluster development, from the embedded phase, to the gas expulsion stage, to the expansion phase, and beyond. Third, clusters exist with extremely different stellar densities, so the ONC might not be representative for the solar birth cluster.

The question is how often do close fly-bys that lead to a significant drop in mass density at 30 au actually happen. This obviously depends on the stellar density in the cluster. Although it seems fairly certain that the Sun formed in a cluster environment, it is still unclear what type of cluster it was (Adams et al. 2014; Pfalzner et al. 2015). Star clusters vary widely in masses and sizes. Here we present our results for a cluster similar to the ONC, because it has been used as an example in previous studies. However, for more compact clusters, like NGC 3603, the fly-by frequency could be considerably higher owing to their higher stellar density. Thus, the presented values here can most likely be regarded as lower limits for the close fly-by frequency. However, the density development in such massive clusters is well constrained by observations (Pfalzner 2009, 2013). In K. Vincke & S. Pfalzner (2018, in preparation) we will give the close fly-by frequency for a variety of clusters, which will put the values presented here in perspective.

3.1. Method

Here only a short summary of the method is given; details including a discussion of the assumptions, are given in Vincke & Pfalzner (2016). The simulations presented here are equivalent to those of model E2 in Vincke & Pfalzner (2016). The clusters were modeled using 4000 simulation particles, corresponding to the estimated number of stars in the ONC. We assumed an initial cluster half-mass radius of \( t_{hm} = 1.3 \) pc, with the initial stellar number density distribution being a relaxed King distribution (W9). For simplicity we neglect potentially existing initial substructuring of the cluster (Parker & Meyer 2012; Craig & Krumholz 2013) in this study. Such substructuring could potentially increase the initial rate of close fly-bys (Winter et al. 2018), so that again our estimate will be quite conservative. However, after the first 2–3 Myr substructuring should be largely erased.

One of the main differences in comparison to other simulations is that we follow the dynamical evolution of such a cluster from the point where star formation has finished, through the gas expulsion phase, resulting in cluster expansion until the cluster reaches an age of 10 Myr. The simulations were performed using the code Nbody6GPU (Aarseth 2003). The cluster was assumed to be in virial equilibrium initially. A star formation efficiency of 30% was modeled, with the gas expulsion taking place instantaneously after 2 Myr. The fly-by history of the first 10 Myr is recorded, at which stage the clusters have found a new quasi-equilibrium state after gas expulsion. Afterward, there is some cluster mass loss owing to ejections and stellar evolution taking place, but this decreases the cluster density by no more than a factor of two. Therefore, the fly-by rate at 10 Myr will be fairly characteristic at least during the consecutive 1 Gyr.

Several simulations with different seeds in the setup were performed to improve the statistical significance of the results. In practice, we start with every star being surrounded by a disk with a size of 500 au, but any other size value would do as long as it is larger than the 30–50 au that we test for. In each simulation, the fly-by history for every individual star is tracked, and the relation given by Equation (2) is then used to determine the system size after coplanar, prograde, parabolic fly-bys. This information is then used to determine the frequency of fly-bys that lead to a disk size of 30–50 au for solar-type stars, which is here defined as stars in the mass range \( 0.8 M_\odot \leq M \leq 1.2 M_\odot \). Inclined fly-bys lead to slightly larger disk sizes than coplanar fly-bys (Clarke & Pringle 1993; Heller 1995; Bhandare et al. 2016), but for a first estimate of fly-by frequency Equation (1) should suffice.

3.2. Results for the Fly-by Frequency

During the first 10 Myr of cluster development, the average stellar density decreases by about 3 orders of magnitude in the cluster. The decrease in stellar density is most dramatic just after gas expulsion, which was assumed to happen at 2 Myr. The decrease in stellar density translates into a drop in the probability of a fly-by that truncates the disk size to the solar system size. This is illustrated in Figure 7, which shows the probability of such a fly-by for solar-type stars. The probability for such a fly-by is highest during the first 3 Myr, after which it is above 10% in the very first few hundred thousand years but drops to a rate of 1%, where it remains during the embedded phase. Note that the value at 1 Myr corresponds roughly to the high end of the frequency estimated by Adams (2010). During the first Myr, 3%–5% of solar-type stars would experience such a fly-by in an ONC-like cluster, and the chance for a close fly-by would increase to about 5%–7% over the first 10 Myr. As such, solar-system-shaping fly-bys are relatively common during that phase. Thus, if Sedna-like objects can form on such short timescales, as some interpretations of the ring structure suggest, a solar-system-forming fly-by would be a relatively frequent event.

However, if Sedna-sized objects need considerably longer than just 1–2 Myr to grow, say, at least 5 Myr, the question arises whether the dramatically decreased stellar density after gas expulsion would still allow for such an event being likely to happen. Figure 7 shows that after 5 Myr the fly-by frequency...
remains more or less constant. Here we take the fly-by probability at 10 Myr as a guideline, because at this age the clusters have reached their new semi-equilibrium state and their density declines only very slowly afterward. Figure 7 shows that the fly-by probability at 10 Myr lies at approximately 0.7%–0.8% per Myr. From long-term simulations of clusters it is known that the density in remnant clusters decreases by about a factor of 2–3 on a Gyr timescale. This means that the fly-by frequency would decrease by the same factor. However, the Sun exists since 4.56 Gyr, so even during the first Gyr every solar-type star would have experienced 0.2–0.3 such events, or in other words, there would have been a 20%–30% probability for such a fly-by during the first Gyr alone. Thus, it is actually likely for a solar-type star to be exposed to such a close fly-by in the long time span that passed since its formation.

One obvious question is, when would this fly-by most likely have happened? Our simulations confirm the earlier result by Malmberg et al. (2011) that although the fly-by rate is highest in the initial phases, this can often be outbalanced by the long time span afterward giving similar probabilities. If we take the values from above, it means that actually the likelihood that the fly-by happened in the later stages was actually a little bit higher than during the first 10 Myr. However, this depends on what type of cluster the Sun actually formed in. If the Sun indeed formed in an ONC-like cluster, a prime candidate for the fly-by would be the time of the late heavy bombardment, since a fly-by would be an extremely good explanation for the large number of impacts. As we saw above, not only does a fly-by lead to matter being excited to more distant orbits, but also some matter is transported inward. A small fraction is transported actually to the inner regions (inside 30 au) of the solar system. However, in how far the properties of this matter correspond to what one expects from that responsible for the late heavy bombardment will need further investigation.

4. Comparison with Other Models

Next, we want to compare the model proposed here with other models that explain outer solar system features. In this comparison we concentrate on the capture scenario and the Nice model. We want to point out that this is not necessarily a question of either/or, but that the capture model and the Nice model are potentially compatible with the scenario we presented above.

4.1. Nice Model

We start with presenting a short summary of the model often referred to as the Nice model (for a more detailed account, including the history of the development of the different variations of the Nice model, see Clement et al. 2018). The hypothesis of the Nice model is that the giant planets formed in a much more compact configuration than their present-day positions suggest. In this model the giant planets moved owing to interactions with a remnant disk: due to conservation of momentum, the outer planets moved outward, because of scattering objects from an exterior disk of bodies preferentially inward. By contrast, Jupiter moved in, because it was likely to eject small bodies from the system in this configuration. As one consequence of the scattering of disk objects, the hot Kuiper Belt formed with its objects moving on eccentric and inclined orbits (Fernandez & Ip 1984; Hahn & Malhotra 1999; Thommes et al. 1999; Gomes 2003; Morbidelli et al. 2005; Tsiganis et al. 2005; Levison et al. 2008; Nesvorný 2015). The Nice model has changed significantly since it was introduced, so that basically an entire family of models exists now, which differ in their initial conditions. They commonly reproduce the hot Kuiper Belt population very well, plus some additional features that vary from model to model.

Originally the Nice model did not give an explanation for the cold Kuiper Belt population, or predict the Sednoids, or explain the higher mass of Neptune compared to Uranus, or necessarily end up with a ninth planet, or explain the newly discovered populations mentioned above. However, by now there are potential explanations for each of these features, although not necessarily in the same model realization. In the early models the stability of the terrestrial planets was problematic; therefore, it was proposed that Jupiter jumped over its 2:1 mean motion resonance with Saturn. It turned out that by starting with a configuration that contains initially more giant planets, the system becomes more stable. This means that, by now, many realizations of the Nice model contain initially five, six, or even seven giant planets. The fact that Neptune is more massive than Uranus is now explained by Neptune and Uranus initially having been positioned in opposite order to today and having swapped places owing to an instability (Kaib & Chambers 2016).

The 10% of the Kuiper Belt objects that move on fairly circular, low-inclination orbits (referred to as the cold Kuiper Belt) is basically not achievable by a scattering process. Therefore, it is now assumed that a cold Kuiper Belt population was produced from a remnant population that was not scattered and located outside Neptune. When Neptune moved outward, this population was moved to more distant orbits, too. However, this only works if Neptune migrates outward quite slowly (Parker et al. 2011; Nesvorný 2015). Recently, an alternative scenario was suggested with a five-planet configuration where the cold population formed in situ, with an outer edge between 44 and 45 au, which never had a large mass (Gomes et al. 2018).

The planets themselves could not have excited the orbits of the Sednoids; an external force is required. One recently revived suggestion for such an external force is the presence of an additional planet on a distant eccentric orbit. There are different possible origins of such a potential ninth planet or planet X. In the context of the Nice model, it has been suggested that one of the additional planets in the initial configuration was excited to this orbit. The newly discovered populations of TNOs mentioned above could be excited to their orbits within the Nice model through combined interactions with Neptune’s mean motion resonances and the Kozai resonance (Sheppard et al. 2016). Thus, we see that there do exist explanations for all these phenomena within the Nice model. However, quite a few processes have to have happened in a certain order.

Comparing the Nice model and the above-described model is not straightforward, for two reasons. First, the Nice model was first suggested in 1984 and has been developed over 30 yr; by now a large body of work exists gradually improving the model to its present day form. Second, the Nice model consists not of a single setup that explains all these observed outer solar system features, but of a family of setups that have in common that they start with a compact configuration followed by planet migration afterward. So one has to keep in mind that this is a
comparison between one single setup and an entire family of model realizations.

The current situation is that the Nice model seems to produce the hot Kuiper Belt population in a long-term development. Note that some authors suggest that so far most N-body simulations do not account for the effects of gravitational interactions between the disk particles themselves (Nesvorný & Morbidelli 2012). This needs to be tested in the future to be sure that the Nice model reproduces the hot Kuiper population well. For the model presented here this long-term development has still to be demonstrated. Hence, in terms of the hot Kuiper Belt population, the Nice model is currently better proven. However, to find an explanation for other outer solar system features, it makes the model more complex and sets increasingly stringent criteria on the initial conditions. Thus, in terms of simplicity the fly-by scenario presented here is at an advantage in comparison to the Nice model.

So far the strongest argument against the fly-by scenario has been the probability of such an event happening. As shown above, this no longer seems so problematic. To put this into perspective, we would have to compare it to the probability of the Nice model. This is very difficult to access, as the exoplanet statistics is still too restricted in the relevant parameter range to give reliable estimates for the probability of finding an initial situation as demanded by the various realizations of the Nice model. However, there have been some estimates for the development of such initial configurations to the current situation in the solar system. There seems to be a 1% chance that the terrestrial planets’ orbits and the giant planets’ orbits are reproduced simultaneously (Kaib & Chambers 2016). The likelihood for Neptune and Uranus swapping places is, at least for the investigated parameter space, very high at 50% (Levison et al. 2008). Thus, the probability of such a realization would be $5 \times 10^{-3}$. Unfortunately, there are no estimates on how often a sufficiently slow movement of Neptune is achieved necessary for retaining a cold Kuiper Belt population. However, there exists an estimate how likely it is that a ninth planet is excited on a suitable orbit, which then could lead to the orbits of the Sednoids. In about 5% of simulations one of the additional planets is excited to a distant eccentric orbit as required for the ninth planet. Thus, if we were to assume that these probabilities are independent, we would obtain in $2.5 \times 10^{-2}$ of all cases a solar system equivalent. This estimate includes neither the likelihood for a slow movement of Neptune nor that for the initial configuration and therefore can only be regarded as an upper limit. More detailed calculations are definitely required for the future. However, taking it at face value, the argument against the fly-by scenario seems not a very severe one, because one could come up with a similar argument against at least this realization of the Nice model.

4.2. Capture Model

As mentioned in the introduction, an alternative suggestion for the origin of the Sednoids is the capture from the outer disk of another star during a close fly-by (Morbidelli & Levison 2004; Kenyon & Bromley 2004; Jílková et al. 2015). Here we compare our results to the most recent ones by Jílková et al. (2015). They performed a parameter study looking for a best fit between the particles captured during such a fly-by and the Sednoids. They assumed that the Kuiper Belt is formed according to the Nice mechanism and that the Sednoids were added by capture during a fly-by. Therefore, the investigated parameter space is restricted to fly-bys that leave the inner 50 au undisturbed, which means that they only investigate fly-bys with periastron distances $b > 265$ au and masses $M_2 < 2 M_J$. They find the best match for the Sednoids for fly-bys of a $1.8 M_J$ star that impacted the Sun at approximately 340 au at an inclination with respect to the ecliptic of 17°–34° with a relative velocity at infinity of $\approx 4.3$ km s$^{-1}$.

First, we only look at the Sednoids and ask the question whether it is more likely that the Sednoids got captured than having originated from the solar system itself in such a fly-by scenario. Actually, the likelihood is about the same, for the following reason: The Sednoids can be captured in a more distant fly-by at 340 au compared to 100 au, which makes such fly-bys more likely. However, this is more than outbalanced by the fact that the star would have a more than 3 times higher mass. As a consequence of the initial mass function, fly-bys of more massive stars are less likely by about a factor of 20. This means that in total the chances for the Sednoids originating from the Sun’s own disk are slightly higher than those for being captured. This is independent of whether the fly-by happened within the first 10 Myr or considerably afterward. When one combines this with the Nice model for the Kuiper Belt, the combined probability is smaller than that for the above-presented model.

4.3. Ninth Planet

Here we want to test whether the existence of a ninth planet would be consistent with a fly-by scenario. It is obvious from above that a potentially existing ninth planet orbiting on a roughly circular orbit could be easily excited to a more distant eccentric orbit owing to a fly-by. However, the question is where that planet would have resided before the fly-by. One suggestion for the rings in observed disks is that forming planets carve these rings into the disks. When one combines this idea with a feature that neither the Nice nor the fly-by model explains, namely, the low fraction of objects in the 50–70 au range, this would be a candidate location for the ninth planet before a fly-by.

From the extension of the surface density one would expect that at 50–70 au a planet would have a mass of 1–2 $M_{\text{Earth}}$. If a planet was located at 50–70 au and cleared this area, we find a 10% likelihood that it would have been ejected. Alternatively, it could have been flung onto a wide eccentricity orbit with a probability of 50%: if it went on an extreme orbit with an eccentricity $>0.8$, this would happen in 5% of all cases. Thus, we would expect a lower mass for a potentially existing ninth planet. Alas, such a low-mass object would probably not have been strong enough to excite the orbits of the Sednoids, but it would be sufficient to stabilize them on their tracks. Thus, a ninth planet and a fly-by scenario would be well compatible.

4.4. Hybrid Models

As mentioned above, the different scenarios discussed here are not necessarily mutually exclusive, but one could also imagine hybrid scenarios. For the capture model, this would naturally result if there were a close fly-by ($\approx 100$ au) as described above, but the perturber would also be surrounded by a disk. In this case, there would be two populations of TNOs, one originating from the solar system and one external. This would be a good explanation for the observed bimodality in the
properties of the TNOs in terms of color. In the future this scenario should be explored in more detail.

In the model presented here we did not consider the situation inside 35 au in the solar system, because this area would be basically unaffected by the fly-bys considered here. Thus, in principle, it is not necessary that the planets inside 35 au were always at their current position, but they could have formed equally well in a compacter configuration. Thus, a close fly-by and the Nice mechanism are not mutually exclusive. In this situation the Nice model could still account for inner solar system features and contribute to the Kuiper Belt population, whereas the fly-by would be responsible for the Sednoids. In this situation the Kuiper Belt would consist of a mixed population, which again would be an explanation for the bimodality of these objects.

5. Summary and Conclusion

Here we investigated the possibility that the orbits of the TNOs were caused by the fly-by of another star. The starting point of our simulations was the Sun surrounded by a disk, which could either be a protoplanetary or a debris disk, possibly containing already-formed planets. We performed an extensive parameter study for the effect of close fly-bys on disks, concentrating on the ones that lead to a steep drop in the mass distribution at 30–35 au as that observed for the solar system. We found that fly-bys of stars with masses in the range of 0.3–1.0 M⊙ at perihelion distances of between 50 and 150 au inclined between 50° and 70° and at an angle of periastron between 60° and 120° are the most promising candidates for a fly-by shaping the outer solar system. Such fly-bys lead to Sednoids, a hot and cold Kuiper Belt population, and various other properties characteristic of the outer solar system. What distinguishes this model from others is that only a single event is necessary to create all these features. Thus, the beauty of this model lies in its simplicity.

In a different set of simulations we determined the likelihood of such fly-bys over time. Here we choose a cluster similar to the ONC as the model environment. Performing simulations of the dynamics of star clusters—gas expulsion, expansion, and finding a new quasi-equilibrium—we find that such types of fly-bys are probable not only during the early phases but also on Gyr timescales, with a 5%–7% chance of all solar-type stars experiencing such a fly-by during the first 10 Myr and a 20%–30% chance in the next Gyr. If planet formation is as fast as anticipated from the ring structures in some disks, even a fly-by during the first 10 Myr would be an option. We showed that the probability of such an event even in the consecutive 4.56 Gyr is competitive with that of other models.

In summary, a close fly-by offers a realistic alternative to the present models suggested to explain the unexpected features of the outer solar system. It should be considered alongside these models as an option for shaping the outer solar system. The strength of this hypothesis lies in its simplicity by explaining several of the outer solar system features by one single mechanism. Thus, this study should be regarded as a first proof-of-principle investigation showing that fly-bys in the parameter range defined above can produce many of the features seen in the solar system. The next steps would be to test within this parameter space for the ideal fit to all the outer solar system features and calculate how the Kuiper Belt population would develop after a fly-by owing to the interactions with Neptune and self-gravity within the disk.

Predictions from this model would be the following:

1. Objects like 2012 VP₁₁₅ should be more common than those with parameters like Sedna and preferentially located at high inclinations.
2. We find that in most close fly-bys not only features similar to the hot Kuiper Belt but also often Sednoid-like populations are produced, though their actual location and population strength vary; similar structures should also exist around many other planetary systems.
3. There should exist considerably more members of the new family of TNOs found by Sheppard & Trujillo (2016) at even larger peristria.

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References
Aarseth, S. J. (ed.) 2003, Gravitational N-Body Simulations (Cambridge: Cambridge Univ. Press), 430
Adams, F. C. 2010, ARA&A, 48, 47
Adams, F. C., Fatuzzo, M., & Holden, L. 2014, ApJ, 789, 86
Andrews, S. M., Wilner, D. J., Zhu, Z., et al. 2016, ApJL, 820, L40
Bailer-Jones, C. A. L. 2018, A&A, 609, A8
Batygin, K., & Brown, M. E. 2016, ApJ, 151, 22
Bhandare, A., Breslau, A., & Pfalzner, S. 2016, A&A, 594, A53
Brasser, R., & Schwamb, M. E. 2015, MNRAS, 446, 3788
Breslau, A., Steinhausen, M., Vincke, K., & Pfalzner, S. 2014, A&A, 565, A130
Breslau, A., Vincke, K., & Pfalzner, S. 2017, A&A, 599, A91
Brown, M. E., Trujillo, C., & Rabinowitz, D. 2004, ApJ, 617, 645
Clarke, C. J., & Pringle, J. E. 1993, MNRAS, 261, 190
Clement, M. S., Kaib, N. A., Raymond, S. N., et al. 2018, Icar, 311, 340
Craig, J., & Krumholz, M. R. 2013, ApJ, 769, 150
Davies, M. B., Adams, F. C., Armitage, P., et al. 2014, in Protoplanets and Planets, ed. H. Beuther et al. ( Tucson, AZ : Univ. Arizona Press), 787
de Juan Ovelar, M., Krijssen, J. M. D., Bressert, E., et al. 2012, A&A, 546, L1
Feng, F., & Bailer-Jones, C. A. L. 2015, MNRAS, 454, 3267
Feng, F., Jones, H. R. A., & Tanvir, T. S. 2017, arXiv:1707.05277
Fernandez, J. A., & Ip, W.-H. 1984, Icar, 58, 109
Gerdes, D. W., Sako, M., Hamilton, S., et al. 2017, ApJL, 839, L15
Gladden, B., Marsden, B. G., & Vanlaerhoven, C. 2008, in The Solar System Beyond Neptune, ed. M. A. Barucci et al. ( Tucson, AZ : Univ. Arizona Press), 43
Gomes, R., Nesvorný, D., Morbidelli, A., et al. 2018, Icar, 306, 319
Gomes, R., Nesvorný, D., Morbidelli, A., et al. 2018, Icar, 306, 319
Gomes, R. S. 2003, Icar, 161, 404
Gomes, R. S., Matse, J. J., & Lissauer, J. J. 2006, Icar, 184, 589
Hahn, J. M., & Malhotra, R. 1999, AJ, 117, 3041
Hall, S. M., Clarke, C. J., & Pringle, J. E. 1996, MNRAS, 278, 303
Heller, C. H. 1995, ApJ, 455, 252
Jewitt, D., Yang, B., & Haghighipour, N. 2009, AJ, 137, 4313
Jilková, L., Portegies Zwart, S., Pijloo, T., & Hammer, M. 2015, MNRAS, 453, 3157
Kaib, N. A., & Chambers, J. E. 2016, MNRAS, 455, 3561
Kenyon, S. J., & Bromley, B. C. 2004, Natur, 432, 598
Kobayashi, H., & Ida, S. 2001, Icar, 153, 416
Kobayashi, H., Ida, S., & Tanaka, H. 2005, Icar, 177, 246
Lada, C. J., & Lada, E. A. 2003, ARA&A, 41, 57
Levison, H. F., Morbidelli, A., Van Laerhoven, C., Gomes, R., & Tsiganis, K. 2008, Icar, 196, 258
