

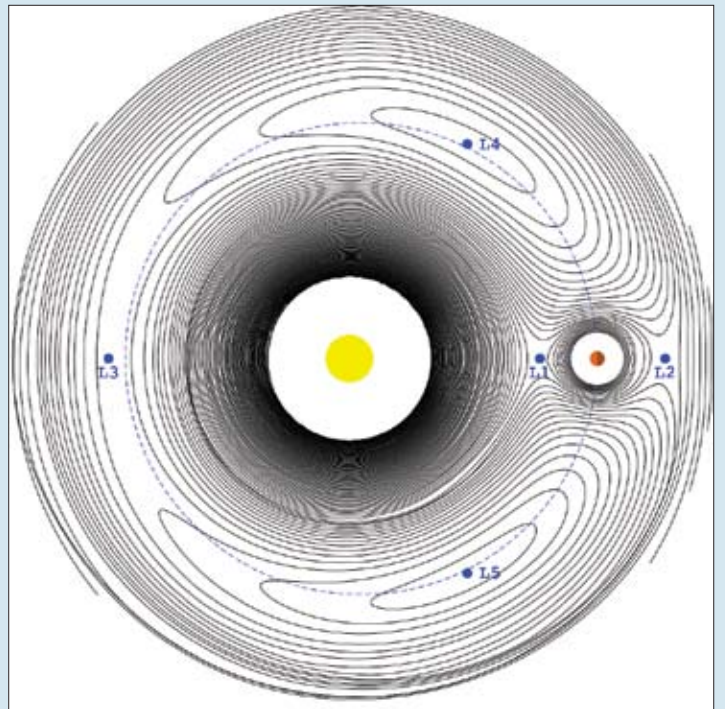
The Neptune Trojans: a window

Jonti Horner and Patryk Sofia Lykawka look at what the leftovers from planet formation reveal about the evolution of both the solar system and other planetary systems.

Seven objects discovered in the past decade might revolutionize our understanding of the formation and evolution of the solar system, as well as provide answers to key questions about its current state. These seven objects comprise the known Neptune Trojans – first members of a population postulated to number as many as 10^6 or 10^7 members greater than 1 km in diameter, which is up to 10 times the number of objects in the asteroid belt up to the same diameter. Much like the Jupiter Trojans, the Neptune Trojans librate around the planet's L_4 and L_5 Lagrange points (large regions of orbital stability located 60° ahead and behind the planet in its orbit, respectively), orbiting the Sun with periods approximately equal to that of the giant planet. Any that leave the Trojan clouds (perhaps nudged through collisions, or perturbed by the distant gravitational influence of other planets) move onto unstable, planet-crossing orbits, where they become indistinguishable from the myriad, unstable, short-lived objects that populate the solar system.

The Jupiter Trojan population is well known and well studied – the first member, asteroid 588 Achilles, was discovered in 1906 and since then several thousand have been found. The Jupiter Trojan population remains somewhat mysterious, however, with considerable debate over its origins and history. Indeed, it seems that the Jupiter Trojans can tell us a fair deal about the way our solar system formed and developed. In the context of planetary formation models in which the solar system formed from a dynamically cold disc (a disc of material moving on orbits with low eccentricities and inclinations), one might expect that any populations of objects that formed from that disc would also move on dynamically cold orbits. For the planets (with the exception of the peculiar Mercury), that indeed appears to be the case – indeed, that observation is a key piece of the evidence that led to the first invocations of modern planetary formation theory, long before any protoplanetary disc had been observed around another star. The orbits of small bodies in the stable reservoirs in the system, however, tell a somewhat more complicated story. Rather than

1: The locations of the five Lagrange points in the restricted three-body problem. In the case of the Neptune or Jupiter Trojans, the brownish planet represents Neptune or Jupiter, with the Sun at the centre. Solid lines connect areas of equal gravitational potential. The regions around the L_1 , L_2 and L_3 points are like saddles, or mountain ridges – small areas in which an object can remain stable, but even a small displacement is enough to make



the object fall out of the stable region. For this reason, satellites at Earth's L_1 and L_2 points carry fuel to make continuous small positional adjustments in order to remain at the "stable" location. By comparison, the regions around the L_4 and L_5 points are broad plateaus, giving large stable regions in which objects can move, free from significant long-term disturbance. As seen in figure 2, the population of Jupiter Trojans, currently several thousand objects (and probably more than one million objects of diameter 1 km or larger) are well contained in these tadpole-like regions, and are thought to have remained in the Trojan clouds since the youth of the solar system. (Figure created using a modified version of the gnuplot code detailed at http://commons.wikimedia.org/wiki/File:Lagrange_points.jpg)

being dynamically cold, the distribution of the orbits of the main belt asteroids, the Jupiter and Neptune Trojans and the trans-Neptunian objects are all distinctly dynamically hot, featuring objects with orbits inclined by tens of degrees to the plane of the solar system, and others with orbits far more eccentric than those of any of the solar system's planets.

Trans-Neptunian objects

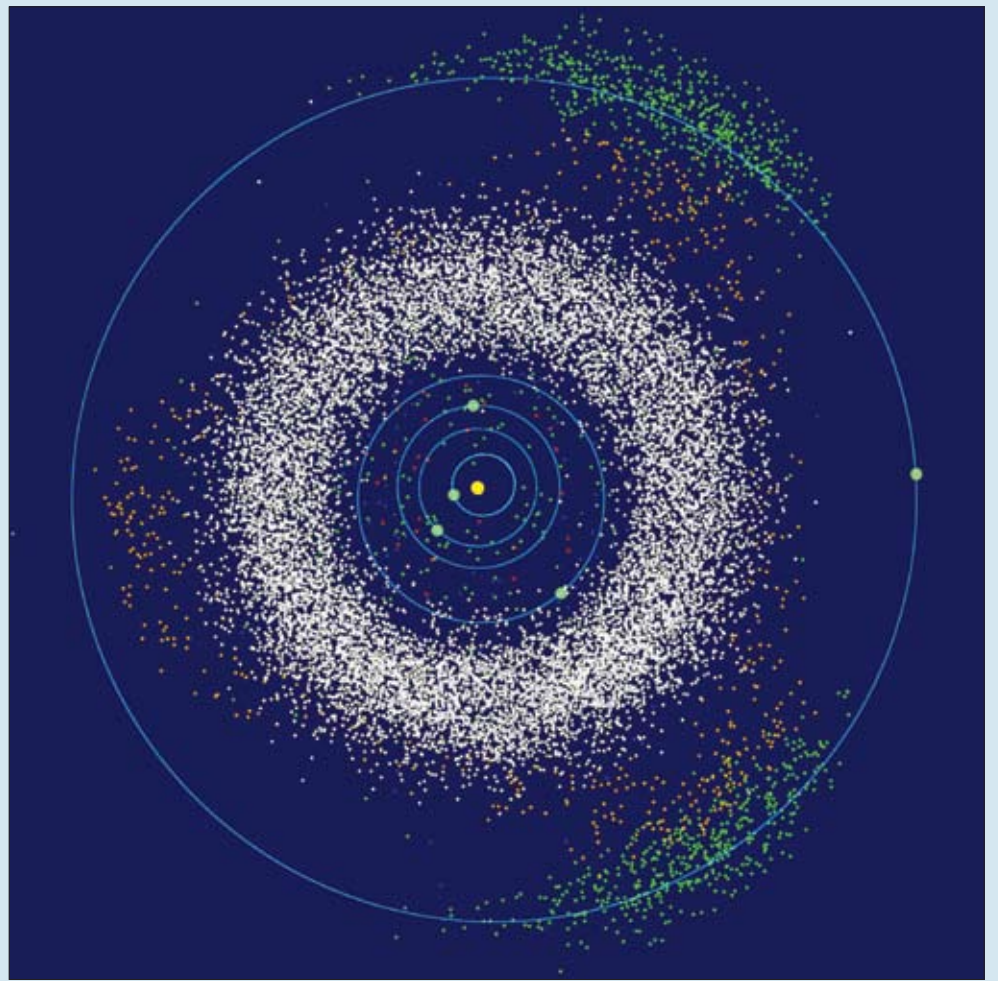
The title "trans-Neptunian objects" collectively describes the members of the Edgeworth–Kuiper belt (often referred to as the "classical disc"), a reservoir of objects that are dynamically stable on Gyr timescales, along with the Plutinos (see below), other families of resonant objects, the Scattered Disc (the less-dynamically stable, more excited counterpart to the Edgeworth–Kuiper belt) and the detached objects, a reservoir of dynamically stable objects at the outer edge of the Scattered Disc, with perihelion distances so great that Neptune can do nothing to destabilize them. This entire complex region is acknowledged as having been heavily

sculpted by the formation and outward migration of Neptune, but a detailed discussion of the interrelation between its various member populations is beyond the scope of this work.

Over the past two decades, the first planets around other stars have been discovered, and those, too, have indicated that planet formation is, at the very least, far more complicated than we previously believed. From models that featured slow and stately planetary growth during which the planets formed at their final locations, models have now evolved to show planets migrating backwards and forwards during their formation, often moving many times further than the distance from the Earth to the Sun. It is believed that our solar system was home to significant planetary migration during its early stages, as the giant planets moved from their initial birthplace in the protoplanetary nebula to their current locations, and that such migration is the cause of the dynamically excited populations of stable bodies we observe today. One key example of this lies in the Plutino population, objects trapped in a 3:2 mean-motion resonance

on the birth of the solar system

2: A view of the inner and middle reaches of the solar system, with the planets denoted by pale green large blobs, and the smaller dots denoting the locations of the near-Earth asteroids (coloured dots interior to the orbit of Mars), the main-belt asteroids (white dots), the Hildas (orange dots; a population of resonant asteroids that complete three orbits around the Sun for every two completed by Jupiter, hence said to be in 3:2 resonance with that planet) and the Jupiter Trojans (clouds of green dots ahead and behind the location of Jupiter, which lies at the right of the plot). Note the "tadpole"-like shape of the Trojan clouds, determined by the structures visible in figure 1. (Modified from public domain image at <http://en.wikipedia.org/wiki/File:InnerSolarSystem.png>)



(MMR) with Neptune (so that they complete two orbits around the Sun in the time it takes Neptune to complete three). These objects, the most famous of which is Pluto, move on a variety of highly inclined and highly eccentric orbits, and it is thought that they were captured to those orbits as a direct consequence of Neptune's outward migration in the latter stages of planet formation. As the giant planet migrated outward, the resonance in which the Plutinos are trapped migrated with it, sweeping up the small objects as it went. Once trapped in the resonance, the objects were swept along with it, with their orbital inclinations and eccentricities becoming ever more excited as they went. Thus the distribution of their current inclinations and eccentricities provides a direct tracer to the distance and speed with which Neptune moved outward – and all indications are that the planet moved by at least 7 AU, and most likely by up to

“The population of Neptune Trojans may prove to outnumber that of the main asteroid belt”

twice that distance (i.e. <15 AU).

Models of planetary formation therefore go to great pains to reproduce the populations of stable small bodies that we know today.

However, there is a problem with this approach – the populations of the asteroid belt, Jupiter Trojans and, to a lesser extent, the trans-Neptunian region are already well known, with fine details of their spread being revealed by the large number of objects known. This means that models of planet formation try to reproduce the distributions observed, rather than making testable predictions about the populations we have not yet found. Modelers test many thousands of potential planet formation scenarios and cherry-pick those which result in the systems that look most like those we observe today.

With the recent discovery of the first Neptune Trojans, however, this picture may now be changing. To date, as we discuss in the fol-

lowing section, just seven Neptune Trojans are known. These bodies are, however, believed to be just the first few members of a population that may even outnumber that of the main asteroid belt. Because that population is, as yet, poorly observed, the time is right to use planetary formation models to make predictions about what the Neptune Trojan population will look like. Predicting the fine details of the Neptune Trojans will therefore allow the different models to be tested, with the large number of Trojans that will be discovered in the near future (by surveys such as LSST, Pan-STARRS and SkyMapper, to name just a few) detailing a whole new stable reservoir in the outer solar system.

The seven new Trojans

Since the discovery of the Jupiter Trojan population, people have wondered whether the other planets could host Trojan populations. Dynamical studies of the outer solar system suggested that the L_4 and L_5 Lagrange points of the orbits of Saturn and Uranus would be dynamically unstable on timescales far shorter than the

lifetime of the solar system, and so no Trojans should be expected for those planets. For Neptune, however, it seemed that these regions could host a stable population of small bodies. However, until the turn of the millennium, none had been found – a case where the theoretical exploration of our solar system outpaced the observational side. Eventually, however, telescopes became sufficiently powerful that the first Neptune Trojan, 2001 QR322, could be discovered. That object was found on a low-inclination, low-eccentricity orbit, librating in the leading Neptune Trojan cloud, around the L_4 Lagrange point. As such, the object seemed to fit nicely with models of solar system formation that assumed that the Neptune Trojans formed *in situ*, and retained the dynamically cold orbital distribution of their parent disc, a result supported by early dynamical studies of that object which suggested it was truly primordial, and highly dynamically stable.

With the discovery of the following six Trojans, however, the situation has changed somewhat. Of the seven Trojans found to date (see table 1), just two move on dynamically cold orbits. The rest move on either moderately or highly ($>25^\circ$) inclined orbits. Given that the surveys that discovered these objects were focused tightly on the ecliptic plane, this result is particularly surprising – even if the Neptune Trojans were isotropically distributed in inclination up to inclinations of 30° , the observation bias of focusing tightly on the ecliptic should lead to the discovery of far more low-inclination than high-inclination bodies. This suggests that, far from being a dynamically cold reservoir of objects that have moved, unperturbed, around the Neptunian Lagrange points since the birth of the solar system, the Neptune Trojans are instead another population of small bodies that bear the scars of planetary migration, just like the Plutinos and the members of the other resonant populations in the trans-Neptunian region.

The dynamics of the known Trojans

Shortly after the discovery of 2001 QR322, two detailed dynamical studies of its orbit were carried out. Those studies, based on the best data available for the object at the time, suggested that the object was dynamically stable on time-scales comparable to the age of the solar system, as would be expected for a primordial Neptune Trojan. In fact, the orbit was so stable that just 10% of a population of objects like 2001 QR322 would be expected to escape from the Neptune Trojan cloud over a period of 4.5 Gyr. Such stability is typical of objects in dynamically stable reservoirs in our solar system, and is part of the evidence that supports those reservoirs being primordial rather than transient features of the system. However, in the decade since the object was discovered, the precision with which the orbit is known has increased signifi-

Table 1: Best-fit orbits of known Neptune Trojans

designation	L_n	a (AU)	e	i ($^\circ$)	A ($^\circ$)	D (km)
2001 QR322	4	30.3668	0.031718	1.322	25 ± 2	100–200
2004 UP10	4	30.2818	0.030633	1.429	12 ± 2	50–100
2005 TN53	4	30.2444	0.065861	24.962	8 ± 2	50–100
2005 TO74	4	30.2545	0.050493	5.244	9 ± 2	50–100
2006 RJ103	4	30.1474	0.027385	8.161	7 ± 2	100–200
2007 VL305	4	30.1186	0.065963	28.085	14 ± 1	80–150
2008 LC18	5	30.0074	0.081998	27.532	15 ± 8	80–150

Here we give the provisional designation of each of the objects, which will be replaced by an asteroidal catalogue number and a name as the objects are better characterized. L_n details the Neptunian Lagrange point about which the Trojan is librating. The next three numbers describe the location and shape of the object’s orbit around the Sun: a denotes the semi-major axis of its orbit (half the major axis of the object’s orbit; for orbits that are almost circular, the semi-major axis is essentially the object’s mean distance from the Sun), measured in astronomical units; e is the eccentricity; and i represents the inclination of the orbit. A details the libration amplitude of the Trojan around its host Lagrange point (along with errors, which are shown at the 1σ level). All Trojans librate, following a path similar to the shapes of the equipotentials shown in figure 1 about their host Lagrange point. Typically, the more stably the object is held at a given Lagrange point, the smaller its libration will be. Finally, D gives the estimated diameter of the object in km, assuming the objects have albedos of 0.05 (upper estimate) or 0.20 (lower estimate). For details, see Horner and Lykawka 2010a,b,c, 2011 and Lykawka and Horner 2010.

cantly, and the best-fit orbital parameters have shifted somewhat as a result of the longer arc of observations available for the determination of its orbit. So the time seemed right to revisit those earlier works and see whether the object truly is as stable as was believed. To do this, we employed an N -body dynamical package called MERCURY, which allows highly detailed dynamical studies to be carried out on reasonable computational timescales.

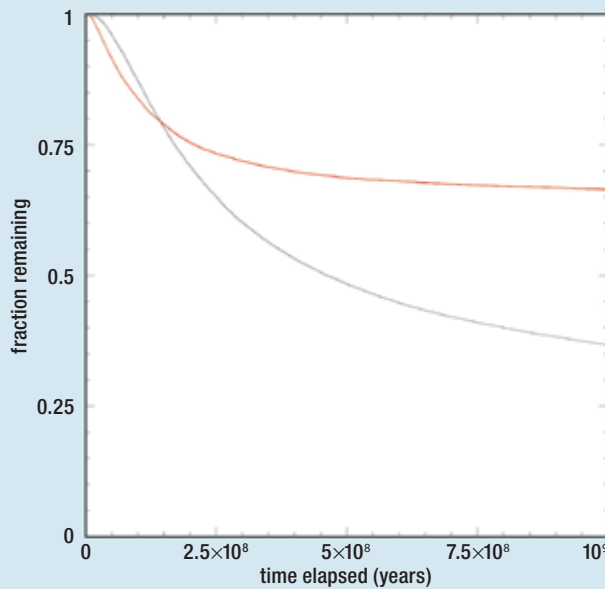
Because of the chaotic nature of orbits within the solar system, simply following the evolution of a single copy of the object will tell us next to nothing about its past and future. Rather, that individual copy will simply play out one of an almost limitless number of potential lives that the real object might experience. We therefore took a statistical approach in order to study the stability of 2001 QR322. Taking the best-fit orbit for the object, we spread 19 683 “clones” of the object about the 3σ error ellipse centred on the nominal orbit, with clones distributed evenly across the ellipse in each of the object’s orbital elements. We then followed the orbital evolution of these clones for a period of 1 Gyr under the gravitational influence of the giant planets Jupiter, Saturn, Uranus and Neptune. The clones were removed from the integration if they reached a distance of 1000 AU from the Sun, or collided with one of the giant planets or the Sun. We followed the number of clones that remained as Neptune Trojans as a function of time, and also recorded the number of clones that survived within the solar system as a whole. Our results were somewhat surprising. Rather than being the dynamically stable object that the earlier studies had suggested, we found that

2001 QR322 is relatively dynamically unstable. Over the 1 Gyr of our integrations, 63% of the clones left the solar system entirely, and just ~35% remained trapped in the Neptune Trojan cloud. The decay of the clones of 2001 QR322 can be fitted by an exponential decay; doing so yields dynamical “half-lives” of 553 Myr (survival as a Trojan) and 593 Myr (survival anywhere in the solar system).

Intriguingly, such dynamical lifetimes are still perfectly compatible with 2001 QR322 being a primordial object, of order one-eighth of the age of the solar system. If we assume that 2001 QR322 is simply the brightest member of a population of dynamically unstable Neptune Trojans, then it would simply require an initial test population of order 256 (2^8) times larger, which seems reasonable in light of the amount of material thought to have remained un-accreted during the latter stages of planet formation (indeed, it has been estimated that the primordial Edgeworth–Kuiper belt contained at least 30 Earth masses of debris – far more than needed for a few objects like 2001 QR322!).

Interestingly, it also turns out that the dynamical stability of 2001 QR322 is a strong function of the initial semi-major axis considered. When we look at the mean dynamical lifetime of the objects and their initial semi-major axis and eccentricity, it is obvious that those clones that began life on orbits slightly closer to the Sun were significantly more stable than those which began life further out. This is a direct result of fine structure within the stability of the Neptune Trojan region. Rather than being uniformly stable, the region is crossed by regions of greater or lesser stability, the result of distant secondary

3: The results of detailed dynamical integrations of 2001 QR322 (in black) and 2008 LC18 (in red) reveal that both objects exhibit significant dynamical instability on timescales of billions of years. Here we plot the survival fraction of “clones” of those objects as a function of time in the outer solar system. The “clones” were massless test particles that were evenly spread around the nominal orbit for the object in question at the start of the integration, distributed so that they cover the full 3σ range of orbital elements possible. While 2001 QR322 displays a decay profile typical of objects in the outer solar system (that can be well fit by a simple exponential decay, yielding a “dynamical half-life” of just under 600 Myr), the decay behaviour of 2008 LC18 is significantly more complicated, a result of the uncertainties in its orbit spanning a sharp disconnect between a very stable and a very unstable region of the Neptune Trojan cloud.



perturbations by the other giant planets. In this case, the region of instability seems to be related to a complex family of secondary resonances between the orbits of the planets Uranus, Neptune and, to a lesser extent, Saturn. The result highlights how important very small shifts in the orbits of objects in the outer solar system can be in determining their stability, but more interestingly reveals a tantalizing possibility: the Neptune Trojan population is continually dribbling away into the outer solar system, continually injecting fresh material to Neptune-crossing orbits. Once an object is placed on a dynamically unstable orbit crossing that of Neptune, it becomes a member of the Centaur population, the bulk origin of which remains in debate.

The Centaurs are a population of dynamically unstable objects moving in the outer solar system. Any object moving on a dynamically unstable orbit with a perihelion that lies between the orbits of Jupiter and Neptune can be considered to be a Centaur, though a number of objects that would otherwise be classified as Centaurs are instead classified as comets, if they were observed to have a typical cometary coma and/or tail at the time of their discovery. The first Centaur discovered, Chiron, is one of the few objects in the solar system to have both an asteroidal and a cometary designation (2060 Chiron and 95P/Chiron), respectively, a result of its outgassing around the time of its last perihelion passage. Regardless of their origin, however, the Centaurs are well established

as being the parent population of the Jupiter-family comets, dirty snowballs that move on orbits of period typically just a few years, with their aphelia near the orbit of Jupiter. If the Neptune Trojan cloud truly has a population 10 times that of the asteroid belt, and the mean half-life of those objects is comparable to that of 2001 QR322, it is easy to show that the population might well represent the single greatest contributor to the Centaur population, and hence to the Jupiter-family comets. Even under more conservative assumptions, where 2001 QR322 is unusually unstable and the population smaller than anticipated, we find that the Neptune Trojans can contribute at least a few percent of the flux required to keep the Centaurs in steady state.

But what of the other Neptune Trojans? Well, having performed similar detailed dynamical studies of their orbits, we find that five of the six remaining are truly dynamically stable, with almost all their clones surviving as Neptune Trojans through the 1 Gyr of our studies. Interestingly, however, the recently discovered 2008 LC18 seems to be another unstable Trojan, albeit on longer timescales than 2001 QR322 (figure 3). Because of the short observational arc available for 2008 LC18, the errors on its best-fit orbit at the current day are significantly larger than those for 2001 QR322, which means in turn that the clones distributed across its error-ellipse span a greater range of orbital elements. As such, it is perhaps unsurprising that we find that part of that error ellipse once again crosses

“Material far from the migrating planets is not immune to their roving influence”

into a region of dynamical instability. The distinction between dynamically stable and unstable orbits for 2008 LC18 is far more clear cut than for 2001 QR322: approximately one-third of the clones tested are dynamically unstable on very short timescales, with the bulk of that population being ejected from the solar system entirely within about 200 Myr. The remaining two-thirds are very stable, with few, if any, ejected even after 1 Gyr. Although this hints that 2008 LC18 might be another unstable Trojan, we must await further observations before we can draw any concrete conclusions.

How did the Trojans form?

During the formation of the solar system, if everything came together in a gentle and sedentary manner, it seems obvious to expect that the debris left over from the planet formation process – the small bodies – would largely reside in reservoirs that reflect that initial distribution. Instead, as mentioned earlier, every stable reservoir of small body in the solar system, including the Jupiter and Neptune Trojans, contains objects on dynamically hot orbits. Such excited reservoirs are precisely what would be expected as a result of planetary migration, as the gravitational influence of the migrating planet stirs and excites the debris within the disc. Significant quantities of that debris are thrown onto unstable orbits, to eventually be ejected from the system or collide with one of the planets, but large amounts can be swept up and stored within stable reservoirs, albeit bearing the dynamical scars of the migration process. The material far from the migrating planets is not immune to their roving influence, with the locations of resonances with the giant planets sweeping through the reservoirs and exciting their contents as the planets move around. Such resonant sweeping has been widely invoked to explain, among other things, the dynamical structure of the asteroid belt (influenced principally by Jupiter) and Edgeworth–Kuiper belt (primarily affected by Neptune).

Turning this concept around, it is clear that if the migration of the giant planets has left its signature on the populations of small bodies in the solar system, then it might be possible to use the particular distribution of those objects to attempt to constrain the properties of the migration itself. A good example here is the Plutino population. As Neptune grew, it began to migrate outward through the protoplanetary disc. As it went, it trapped objects from that disc in its 3:2 MMR, creating the Plutino population. The further the planet migrated, the greater the levels of inclination and eccentricity excitation those Plutinos first captured experienced, resulting in the population we observe today. Because of this migration-driven pumping, if we study the precise distribution of the Plutinos at the current epoch, it is possible, to some extent,

to untangle both the speed and distance over which Neptune migrated, as well as drawing some conclusions on the stochasticity of that migration (i.e. was it smooth or jumpy?).

The Nice models

The most prominent models for the formation and migration of the giant planets in our solar system are known collectively as the Nice models. They attempt to explain a wide variety of the solar system’s features, from the distribution of objects in the asteroid belt and the extremely excited Jupiter Trojan population, to the putative “Late Heavy Bombardment” (LHB). The models suggest that the four giant planets formed in a much more compact architecture than we currently observe. Interior to the orbit of Jupiter, and exterior to that of the outer planet, lay reservoirs of small bodies left over from the system’s formation, containing vast amounts of material. According to these models, the region beyond the outermost planet, in particular, contained approximately 35 times the Earth’s mass in icy bodies. Over time, the outermost planet perturbed that disc, sending material from it into unstable orbits crossing those of the giant planets. As a result of the conservation of angular momentum, as the planet transferred icy bodies inwards, it migrated outwards, moving further and further towards the inner edge of the belt and perturbing ever more objects.

Conversely, at the inner edge of the outer solar system, Jupiter is by far the most efficient of the planets at ejecting such objects from the solar system – the final fate for the great majority of such unstable bodies. Again, as a result of the conservation of angular momentum, this role made Jupiter migrate slowly inwards. This slow migrational spreading of the outer solar system is suggested to have continued in a fairly slow and sedate fashion for a few hundred million years until Jupiter and Saturn approached and then crossed one of their mutual mean-motion resonances. This resonance crossing dramatically destabilized the outer solar system, flinging Uranus and Neptune into the massive disc of particles beyond them. Because of the great mass of leftover material in that disc, dynamical friction quickly circularized their orbits, in the process scattering many Earth-masses of material to the inner solar system, causing a spike in the impact rate at the terrestrial planets.

This highly dramatic suite of models do a remarkable job of explaining the various features of the solar system as we observe it today. This is not, however, totally surprising, since the models are chosen from tens of thousands of trial “potential solar systems” to see which best fit the various observed properties of the solar system as we know it today.

One of the key motivations for the inception of the Nice models is to provide a dynamical explanation for the putative LHB of the inner

solar system. The LHB is a proposed dramatic spike in the impact rate experienced by the terrestrial planets approximately 700 Myr after the formation of the solar system. The idea first came to light in the early 1970s, in an attempt to explain the formation epochs of the various samples brought back to the Earth by the lunar missions. The theory states that the Moon suffered dramatic impacts at around 3.8 Gyr ago which led to the formation of the great majority of the lunar mare. Although the idea of the LHB is widely accepted within the astronomical community, there remains significant debate about it in other fields. Geologists argue that there is no evidence to be found on the Earth of the putative bombardment, while recent work reinvestigating the materials brought back from the Moon have also cast doubt on the interpretation that the lunar mare were all formed in one short, sharp burst around 3.8 Gyr ago. Indeed, many researchers suspect that the LHB never actually happened, but instead believe that the impact rate in the inner solar system fell away rather more gradually over the first hundred million years of the system’s evolution, reaching a rate vaguely similar to that we observe today at around the time postulated for the end of the LHB. Given that the LHB itself is still under debate, it seems reasonable to consider other more stately scenarios for the formation and migration of the outer planets. If we remove the requirement that something dramatic had to happen some 700 Myr after the system formed, it opens up a wide range of less stochastic and more gentle scenarios that could also explain the system as we see it today. We discuss some such scenarios below.

When considering models of planetary formation and migration, is it important to consider how the various scenarios relate to the Trojan populations, particularly the highly dynamically excited Neptune Trojans? While the other reservoirs of material known within our solar system are well studied and their distributions tightly constrained, the Neptune Trojans are still poorly detailed, with just seven members to date. Although that does allow some conclusions to be drawn, particularly given the biases inherent in the discovery surveys, it is fair to say that the fine structure and detail of the Neptune Trojan cloud remains to be revealed. They therefore represent an ideal predictive test-bed for the various models of planetary formation and evolution. Did the Neptune Trojans form *in situ*, to be carried with the planet as it migrated? Were they instead captured (like the Plutinos) during that migration? What distribution of objects would we expect if the migration of Neptune was fast, or more sedate? By comparing the

expected distributions that result from such formation scenarios to that we observe today, we have an extra constraint by which the various models can be compared. Beyond that, however, the models can be used to make predictions: if scenario X represents the true origin of the system as we see it today, then future observations will reveal a Trojan population distributed like this, while if scenario Y is true, then the actual distribution would look something like that.

As a first step along that road, we decided to consider the evolution of the Neptune Trojan population as a function of Neptune’s migration, investigating a suite of scenarios in which that migration was smooth and gentle. Although the Nice models consider scenarios in

“We considered the evolution of the Neptune Trojan population as a function of Neptune’s migration”

which the first stage of migration is highly chaotic, they also regularly feature a second stage of migration in which Neptune moves in a fairly sedate and smooth fashion from ~25 AU to its current location. This means that our smoothed migration integrations may also be considered compatible with the evolution shown in the

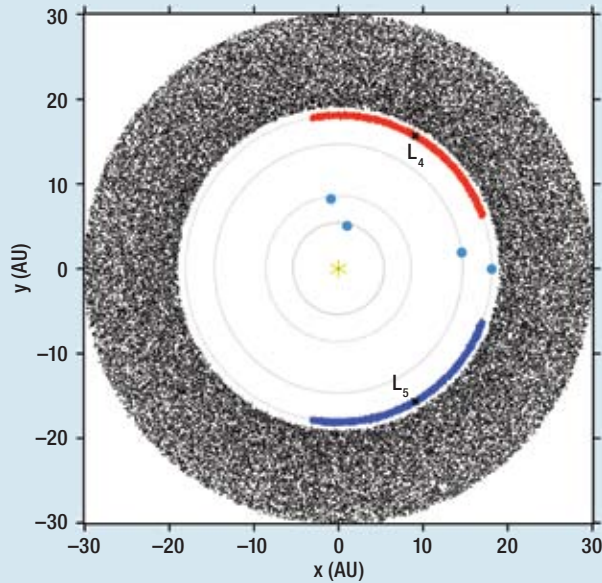
Nice models, albeit after the chaotic migration phase. If such smooth migration can produce the kind of distribution that is observed, it can be taken as evidence that such dramatic planetary evolution is not required in order to reproduce the formation conditions of the Neptune Trojans seen today.

Our formation runs

In order to model the formation of the Neptune Trojans, we carried out several distinct suites of dynamical integrations. In order to span the various models of non-chaotic planetary migration spread through the recent literature, we considered scenarios in which the migration of Neptune was fast (taking just 5 Myr to migrate from its origin to its final location) and slow (taking 50 Myr to make the same journey). We considered cases where Neptune migrated over a relatively short distance (from 23 AU to its current home at 30 AU) and others where it migrated much further (from 18 AU to 30 AU). The migration of the other giant planets was also incorporated into these models, with the planets migrating in a smooth fashion, exponentially approaching their final locations. Taken together, this gives four main migration scenarios, which we describe as 18F, 18S, 23F and 23S, where the number refers to the initial location of Neptune, and the letter F or S refers to fast or slow migration. For each of these scenarios, we ran detailed integrations following the fate of clouds of pre-formed Neptune Trojans (i.e. Trojans that formed *in situ*), moving on initially highly dynamically cold orbits librating around the planet’s leading and trailing Lagrangian

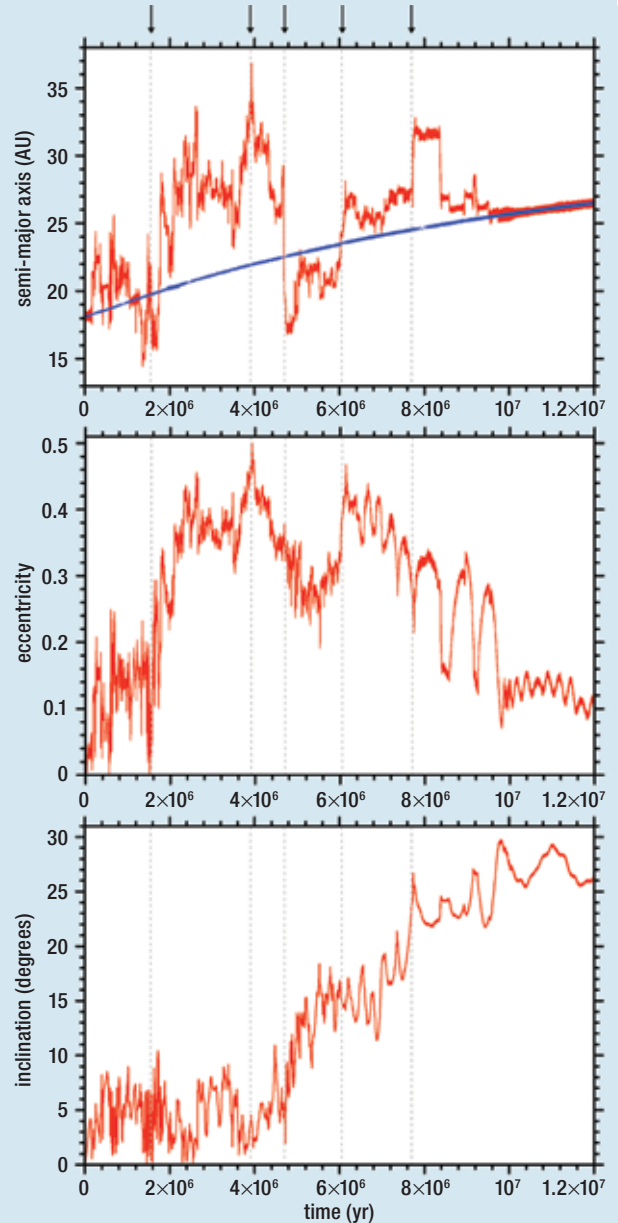
EXAMPLE RESULTS FROM NICE MODELS INVOLVING A MIGRATING NEPTUNE

4: The typical initial conditions used in our simulations of the influence of Neptune's migration on its Trojan population. Though the initial setup for each scenario considered would look the same, the particles plotted here are from a study in which Neptune began migration at a distance of 18.1AU from

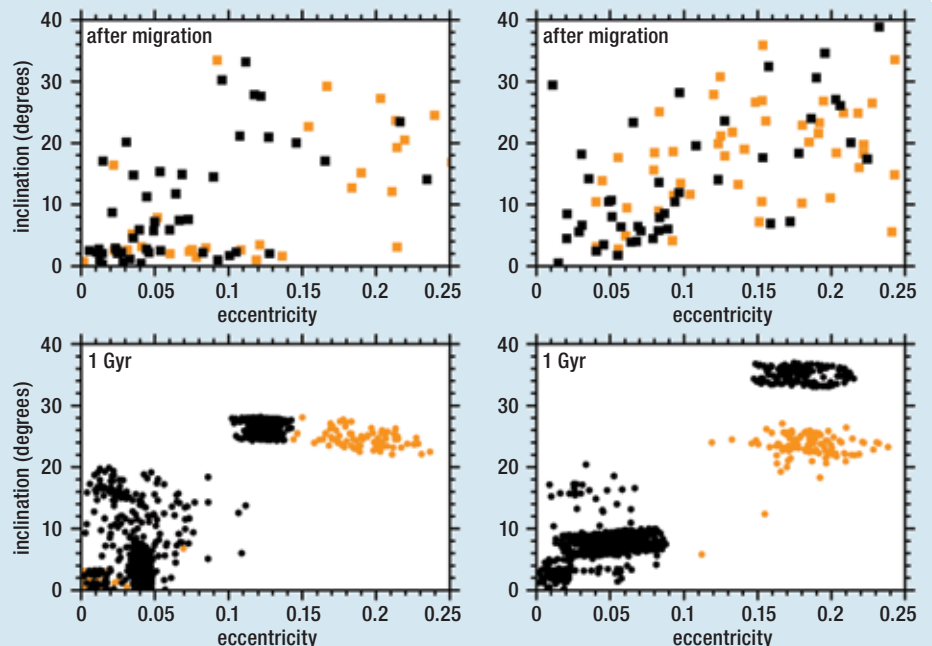


the Sun. Objects representing the pre-formed Trojans around the L_4 Lagrange point are marked in red, those around the L_5 point in blue, while the objects in the trans-Neptunian disc are shown in black. The pre-formed Trojans were placed with an initial displacement of up to 40° from their Lagrange point, while the disc of objects was distributed on orbits distributed between 1AU beyond the orbit of Neptune and 30AU from the Sun (Neptune's final resting place). All particles considered were placed on initially dynamically cold orbits, with $e \sim i < 0.01$.

6 (right): An example of a pre-formed Trojan being first lost, then recaptured, from the Trojan cloud during the slow migration of Neptune from 18.1AU. The plots detail the first 12Myr of the object's evolution, with its semi-major axis, eccentricity and inclination being plotted at top, middle and bottom, respectively. The evolution of Neptune's semi-major axis is shown in the upper panel (blue curve). The object escapes from the Neptune Trojan cloud early in the simulation, as can be seen by its semi-major axis moving away from that of Neptune. Once it has escaped from that region, the object experiences a number of close encounters with Uranus and Neptune, which are marked by sudden large changes in the orbital elements. We have marked some of the more prominent encounters on the plot, as vertical dashed lines. Finally, the object is recaptured to the Trojan family, albeit with greatly excited inclination, where it remains for the final 40Myr of Neptune's migration.



5 (right): The distribution of Neptune Trojans resulting from our calculations for a scenario in which Neptune slowly migrated outward from a heliocentric distance of 18.1AU to its current location at 30AU. The upper panels show the distribution of objects at the moment migration ceased. The survivors shown in that plot were used as the basis for a much larger test population of objects intended to replicate the immediate post-migration Trojan clouds. The distribution of those objects after 1 Gyr of dynamical evolution under the gravitational influence of Jupiter, Saturn, Uranus and Neptune can be seen in the lower panels. The points in black represent true Trojan objects, while those in orange denote either objects moving on horseshoe orbits (a typically less stable Trojan configuration, in which the object's libration takes it around both the L_4 and L_5 Lagrange points, and also around the L_3 point at the far side of the Sun from the planet) or "sub-Trojan" orbits, which are orbits located close to the peripheries of the Trojan cloud without lying within it.



points (figure 4). We then ran separate integrations in which the planets migrated in exactly the same fashion, but rather than hosting a population of pre-formed Trojans, Neptune was instead migrating outwards through a disc of test particles designed to resemble the disc of material expected to remain beyond the orbit of that planet at the end of its pre-migration formation. For simplicity, the masses of the planets were held constant through their migration. The Neptune Trojan population at the end of migration was then sampled and compared to that seen today (figure 5).

Several features are immediately apparent upon examination of our formation runs. Firstly, of the scenarios in which the evolution of pre-formed Trojans was considered, only one was able to even vaguely reproduce the dynamically excited population of Neptune Trojans we observe today. For the other three cases, the retention of Trojans was highly efficient, with few, if any, being lost. In the case in which the transported population appears to have experienced dramatic excitation, however, the great majority (over 99%) of the particles escaped from the Trojan cloud as a result of the planets Uranus and Neptune undergoing a period of mutually resonant behaviour, which acted to destabilize the Trojan clouds. Indeed, those objects that are seen as Trojans at the end of the simulations, which make up just a fraction of a percent of the initial population, are essentially captured objects, having initially escaped from the Trojan clouds before being recaptured after protracted periods evolving on dynamically unstable orbits (figure 6).

When it comes to the scenarios in which captured Trojans were considered, the picture is more promising with regards to reproducing the observed distributions. In all scenarios, a dynamically diverse population of Neptune Trojans are captured, albeit on orbits that struggle to reproduce the members of the current population observed on orbits of very low eccentricity but high inclination. Nevertheless, those models seem to provide a far better fit to the observed population of objects than those that invoke the transport of pre-formed Trojans. The capture efficiency displayed in those runs (between 0.1 and 1%) might initially seem low. However, we remind the reader that Neptune would have been migrating outwards through a vast population of small bodies, containing many tens of Earth masses of material. As such, even a capture efficiency of 0.1% would be sufficient to produce a vast initial population of objects trapped as Neptune Trojans.

Interestingly, the results of these admittedly simplified initial simulations suggest that the Neptune Trojans, like the Plutinos, are a popula-

tion which was captured as a result of Neptune's migration, rather than having formed with the planet and being then transported with it. Furthermore, it is interesting that our results show the possibility of capturing a highly excited population of bodies with a gentle, smooth migration (a result we recently showed also holds true for the Jupiter Trojans). At least as far as the Jupiter and Neptune Trojans are concerned, it seems that the high chaos of the Nice models is not required to reproduce the observed distribution. But it is clear that further work must be carried out to examine a wider range of the scenarios invoked in order to examine in detail the formation and evolution of our planetary system. Such work will allow predictions of the true distribution of Neptune Trojans to be tested observationally as more are discovered.

“The Trojans represent an exciting opportunity to test models of planetary formation and evolution”

Conclusions

The Neptune Trojans represent the latest exciting addition to the menagerie of solar system bodies. A population of just seven discovered objects, it is postulated that the total might outnumber that of the asteroid belt by up to an order of magnitude. The population offers an exciting fresh opportunity for testing models of Trojan formation.

The seven known Trojans are interesting in themselves. Rather than being the expected dynamically cold suite of objects, they exhibit a wide range of orbital inclinations, with three of the seven possessing orbits inclined by more than 25° to the plane of the ecliptic. Despite this, five of the seven objects move on orbits that are dynamically stable over the age of the solar system. The other two lie close to regions of instability within the Neptune Trojan clouds, such that at least some of the potential orbits that fit their observed properties exhibit significant dynamical instability. As well as being a reminder that even the dynamics of theoretically highly stable regions of the solar system feature surprising fine structure, this opens up the tantalizing possibility that the Neptune Trojans as a whole (including objects with decay lifetimes on the order of gigayears) might represent a significant source reservoir for the Centaur population and their daughters the Jupiter-family comets. In other words, a significant fraction of the known Jupiter-family comets might well have originated in the Neptune Trojan cloud, with new members continually being sourced from that region to replace those that are ejected from the solar system, disintegrated as their volatiles are depleted, or collide with one of the planets or the Sun.

The Trojans as a whole also represent an exciting opportunity to test the various models

of planetary formation and evolution, many of which were developed before the discovery of the excited Neptune Trojans. If those models represent a true description of the way our solar system formed and evolved, then they should be able to predict the distribution of Neptune Trojans that will be discovered in the future. In particular, this allows us to revisit the question of chaotic versus gentle planetary migration. The Nice models, developed in part to explain the putative (but still heavily debated) Late Heavy Bombardment of the inner solar system, do a remarkable job of explaining the many fine details of the solar system as we observe it today, and offer explanations for the dynamically excited distribution of the Jupiter and Neptune Trojan populations. The more gentle scenarios proposed elsewhere, in which the migration of the outer planets is a significantly smoother process, could in theory be expected to have some difficulty explaining the origin of the dynamically hot Neptune Trojan population. However, we have shown that it is possible to produce dynamically excited populations of captured Jupiter and Neptune Trojans as a result of smooth and sedate planetary migration – showing that, for these Trojans at least, the catastrophic and chaotic scenarios put forward by the Nice group are not necessarily the only answer.

Over the next decade, the number of known Neptune Trojans will likely grow dramatically as the next generation of surveys (including Pan-STARRS, SkyMapper and the LSST) come online. The time is therefore ripe for models of planetary formation and evolution to move beyond simply attempting to explain everything we already see in the outer solar system and instead attempt to predict the distribution of Neptune Trojans that we should expect to see in the coming years. The seven objects that have already been detected have thrown up a number of surprises already, and it is likely that many more surprises lie ahead as the population is uncovered in all its glory. ●

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Further reading

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