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On the origin of the unusual orbit of Comet 2P/Encke

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Abstract

The orbit of Comet 2P/Encke is difficult to understand because it is decoupled from Jupiter—its aphelion distance is only 4.1 AU. We present a series of orbital integrations designed to determine whether the orbit of Comet 2P/Encke can simply be the result of gravitational interactions between Jupiter-family comets and the terrestrial planets. To accomplish this, we integrated the orbits of a large number of objects from the trans-neptunian region, through the realm of the giant planets, and into the inner Solar System. We find that at any one time, our model predicts that there should be roughly 12 objects in Encke-like orbits. However, it takes roughly 200 times longer to evolve onto an orbit like this than the typical cometary physical lifetime. Thus, we suggest that (i) 2P/Encke became dormant soon after it was kicked inward by Jupiter, (ii) it spent a significant amount of time inactive while rattling around the inner Solar System, and (iii) it only became active again as the ν_6 secular resonance drove down its perihelion distance.

1. Introduction

The periodic Comet 2P/Encke is one of the most mysterious and befuddling objects in the Solar System. 2P/Encke is a bright, low-inclination comet on an orbit with a surprisingly small aphelion distance (Q) of only 4.1 AU. As such, although similar to Jupiter-family comets (JFCs, comets with Tisserand parameters with respect to Jupiter, T, between 2 and 3; see Levison, 1996) in other respects, 2P/Encke is dynamically decoupled from Jupiter. Numerical integrations of its orbit show that 2P/Encke will hit the Sun in only 10^5–10^6 yr (Levison and Duncan, 1994) due to its close association with the ν_6 secular resonance (Valsecchi et al., 1995). The origin of 2P/Encke is a puzzle, since the evolution of a JFC onto an orbit with such a small aphelion distance is not well understood (see Valsecchi, 1999, for a review).

The importance of understanding the origin of 2P/Encke goes well beyond interest in a lone, odd object. There are several kilometer-size asteroids known to be in orbits similar to 2P/Encke (Asher et al., 1993). These small 'asteroids' could indeed be extinct comets. If 2P/Encke is the only known active member of a significant population of extinct comets, then this population could be responsible for a significant fraction of the near-Earth objects (NEOs) and thus a significant fraction of Earth's impactors. Indeed, Kresák (1978) and Asher and Steel (1998) have pointed out similarities between the Tunguska object and meteoroids that are associated with 2P/Encke (although see Farinella et al., 2001 for an alternative perspective).

Currently, it is believed that the vast majority of Earth's impactors are asteroidal (Bottke et al., 2002). However, the models that led to this conclusion made use of the simulations in Levison and Duncan (1997) (hereafter LD97). LD97 studied the evolution of ecliptic comets ($T > 2$; see Levison, 1996, for a complete definition) from the Kuiper belt, through the outer planetary region, to visible JFCs. During these simulations, no objects were produced that had orbital elements similar to those of 2P/Encke, presumably because these integrations did not include the gravitational effects of the terrestrial planets nor non-gravitational (NG) effects due to cometary activity. Thus, the models in Bottke et al. (2002) did not include a possible Encke-like source. In principle, since Bottke et al. (2002) argued that many NEOs evolved through the ν_6 resonance on their way to their current orbits, and 2P/Encke is associated with this reso-

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nance, many NEOs could be extinct Encke-type comets. Thus, solving the 2P/Encke problem could lead to a change in our understanding of the relative importance of asteroids versus comets in the impact hazard.

In order to determine whether dynamical pathways exist between 2P/Encke and the Jupiter family, Valsecchi et al. (1995) integrated the trajectories of a small number of real asteroids with Encke-like orbits. Their goal was to follow objects 'backward' in time to their source regions. They included the terrestrial planets in their simulations, but not NG forces. They found that some objects evolved onto orbits similar to those of the JFCs, but the timescales were longer than the physical lifetime of a comet. Thus, it is unlikely that a comet evolving in the 'forward' direction would be active after the process was complete. Steel and Asher (1996) performed a similar set of integrations in which they crudely included NG effects. They also found that some of their objects evolved onto JFC-like orbits. In addition, they found more reasonable (i.e., shorter) timescales. Since both these simulations integrated 'backward' from Encke-type orbits to the Jupiter family, the authors were unable to estimate the likelihood that the 'forward' process would indeed occur.

So, these early works showed that there are two dynamical pathways between the Jupiter family and Encke-like orbits—one without NG forces but with terrestrial planets and one with NG forces. However, because they were backward integrations they could not determine which pathway is really the most important or whether either is efficient enough to explain 2P/Encke's existence. These questions can be answered only with forward integrations. We discuss each dynamical pathway separately.

Forward integrations without NG forces were performed by three groups. Harris and Bailey (1996) followed the evolution of 360 fictitious Jupiter-family comets. All 360 objects had perihelion distances, q, of 1 AU and $Q = 5.2$ AU. Their initial inclination, i, was set to 0, thereby artificially enhancing the gravitational effects of the Earth. The orbital evolution of these objects was calculated under the gravitational influence of the Sun and all the planets except Mercury and Pluto. They found that 2 of the 360 objects became decoupled from Jupiter (i.e., $Q < 4.2$ AU), and those for only short periods of time.

A more realistic study was performed by Fernández et al. (2002) (hereafter FGB02), who studied the evolution of 202 known Jupiter-family comets. They found that only 1 of their 202 objects decoupled from Jupiter (a fraction similar to that of Harris and Bailey, 1996). Comparing the dynamical lifetime of this object to that of the JFCs as a whole and using an estimate of the total number of JFCs by Fernández et al. (1999), they concluded that there is a 25% chance that the Solar System would contain an Encke (which they defined as any active comet with $Q < 4.2$ AU, see below) at any given time if one only considered purely gravitational effects. This number is reasonable given that both the observational data and the model suffer from small number statistics, i.e., they are based on one object in each case. So, these works seem to imply that the purely gravitational dynamical pathway can work.

Finally, Ipatov and Mather (2003) also looked at the rates at which objects decoupled from Jupiter. Their results seem to be inconsistent with our results and with the other works described above. We will discuss these inconsistencies in Section 3 and speculate on why they exist.

FGB02 also performed simulations where NG forces were included. They found that NG forces could decouple objects much more effectively than gravity alone. Indeed, for NG forces similar to those historically acting on 2P/Encke, they found that we should expect a steady state population of $\sim$10 Encke-like objects. Although this sounds like a reasonable number, they also found that this force must be applied for at least 10^5 yr, which is probably too long considering that comets probably only remain active for $\sim 10^4$ yr (Whipple and Sekanina, 1979; LD97). FGB02 also show that they can make Enckes in $\sim 10^4$ yr if they increase the NG forces by a factor of 10 (Harris and Bailey, 1996, found a similar result), but they argue that it is unlikely that a comet would remain so active for this length of time. Thus, we are left to question whether NG forces can indeed work.

Pittich et al. (2004) performed a similar set of integrations to those in FGB02, but produced Encke-like objects in only 10^4 yr thereby apparently solving the problem. The main difference between these works is that FGB02 allowed the magnitude and direction of their NG forces to vary with time, while Pittich et al. (2004) held their NG forces constant. We believe that it is unphysical to assume that the NG forces are constant for thousands of years, because cometary activity is observed to change on a much shorter timescale (Sekanina, 1993). This is particularly true for Comet 2P/Encke since its NG accelerations have been observed to change over historical times (Marsden and Sekanina, 1974). Thus, we believe that Pittich et al. (2004) significantly overestimated the role of NG forces.

So, we seem to be in a state of uncertainty about which dynamical process is responsible for the unusual orbit of Comet 2P/Encke. One significant problem with the works described above is that they only employ a small number of particles. Here, we revisit the issue of the purely gravitational problem with a simulation that follows the dynamical evolution of what is effectively 660,000 particles from the trans-neptunian region inward. Our goal was to redo the simulations in LD97 with improved initial conditions and with the terrestrial planets, in order to address several issues, including the origin of 2P/Encke's orbit. The other issues will be addressed in a future paper. Here, we address the problem of 2P/Encke. In Section 2 we present our numerical methods and initial conditions. In Section 3 we describe our results. We conclude in Section 4.

Before we proceed, we have a comment on notation. At several points in this paper, we compare our models with observations. To perform such an analysis, we must correct for observational selection effects. To do this completely is beyond the scope of this paper. Thus, we adopt the convention developed by Duncan et al. (1988) and used in Levison and Duncan (1994) and LD97, which assumes that all active comets with $q < 2.5$ AU have been discovered, while those with $q > 2.5$ AU have not. For the remainder of this paper, we refer to comets with $q < 2.5$ AU as visible comets.

2. Numerical methods

As stated above, LD97 studied the evolution of objects from the point where they first encountered Neptune until they hit the Sun or a planet, were ejected from the Solar System, or evolved into the Oort cloud. Their goal was to understand the entire ecliptic comet population, including the scattered disk (Duncan and Levison, 1997), the centaurs, and the JFCs. It is this type of simulation that is best for studying the origin of Encke's orbit because it supplies us with unbiased initial conditions. FGB02 used the known JFCs, which are biased toward small perihelion distances, as their starting point, while Harris and Bailey (1996) only studied a very narrow range of objects—those with $q = 1$ AU, $Q = 5.2$ AU, and $i = 0°$.

However, the simulations in LD97 suffered from their own limitations. First, they did not include the terrestrial planets nor NG forces. Thus, they cannot be used to study the origin of Encke's orbit. In addition, when LD97's initial conditions were constructed, it was assumed that the Kuiper belt consisted of objects on low-inclination orbits, i.e., that the Kuiper belt was dynamically cold. While this was a reasonable assumption at the time, it is now known that the Kuiper belt is dynamically excited (see Morbidelli et al., 2003, for a review). Thus, we set out to redo LD97 with more reasonable initial conditions and with the terrestrial planets included.

In particular, we generated the initial conditions for our main simulations using the following technique. We integrated the orbits of 1200 particles initially in the Kuiper belt for 4 Gyr or until they either entered Neptune's Hill sphere or evolved beyond 1000 AU. The particles were initially uniformly spread in semi-major axis between 41 and 47 AU, had eccentricities between 0 and 0.27, and inclinations up to 32°. From these simulations we randomly chose 11 particles from the set of objects that were removed from the simulation because they entered Neptune's Hill sphere, but that had survived for at least 2 Gyr.

Before we proceed, we need to discuss an assumption we are making in generating our initial conditions—the Kuiper belt is the source of the centaurs and JFCs. This was a reasonable assumption when we started these simulations, but more recently Duncan et al. (2004) convincingly argued that an ancient scattered disk was most likely the source for these objects. However, once a particle evolves onto a Neptune-crossing orbit all memory of where it came from is erased except for information contained in its Tisserand parameter with respect to Neptune, T_{N}. So, our initial conditions are reasonable as long as the T_{N} distribution of our particles is similar to that of the scattered disk. Our particles have a median T_{N} of 2.87, while the observed scattered disk has a median T_{N} of 2.91 (we only included scattered disk objects with perihelion distances between 25 and 32 AU in this calculation). Thus, we think our initial conditions are reasonable even if the scattered disk is the source of the centaurs and JFCs. We now continue with the description of our methods.

Each of our chosen 11 particles had to be integrated in separate runs, since they all left the Kuiper belt at different times and thus the planets were in different locations. Each particle was cloned 199 times by adding a uniformly distributed random number between $\pm 2 \times 10^{-7}$ AU to each of the positional coordinates of the particle. The orbits of the clones were integrated under the gravitational influence of the Sun and the four giant planets using the *RMVS3* integration scheme (Levison and Duncan, 1994). Our integration scheme is based on the method of Wisdom and Holman (1991), but additionally it can handle close encounters between particles and planets. We used a timestep of 0.025 yr or ∼9 days. The effects of non-gravitational forces were not included. In all, the orbits of 2200 particles were integrated.

The trajectory of a particle was again followed for 4×10^9 yr unless it was ejected from the Solar System, impacted the Sun or a planet, or reached a semi-major axis of 1000 AU. We stopped following a particle at $a = 1000$ AU because galactic tides and passing stars begin to have significant dynamical effects at this distance (Duncan et al., 1987). Presumably, most of these objects will eventually become part of the Oort cloud or be ejected from the Solar System.

From the previous works (Harris and Bailey, 1996; FGB02), we expect that only a small fraction of our original particles should evolve onto Encke-like orbits. In addition, we wanted to make sure that we did not miss some very rare, but long-lived dynamical pathway. Thus, during our simulations a particle was cloned 299 times the first time it reached a perihelion distance less than 4 AU. So, we are effectively integrating the orbits of 660,000 particles from the trans-neptunian region.

3. Dynamical pathways to Comet 2P/Encke's orbit

We start our analysis by studying the effects that terrestrial planets have on the final steady state distribution of comets in the inner Solar System. Fig. 1 shows a comparison between the results from LD97 (without terrestrial planets) and that of the current simulations. The contours in the figure are generated assuming that the rate of objects leaving the Kuiper belt has remained approximately constant over recent times and it does not take into account the physical evolution of the comets (this is discussed in more detail below). The figure was generated by placing the comets at all output times in the integration into q–Q bins that were 0.12 AU on a side. The resulting matrix was then normalized so that the total number of objects with semi-major axes less than that of Jupiter and $Q < 6$ AU was equal to one. At this point in the discussion the scaling is irrelevant. The only important issue is that the two panels of Fig. 1 were scaled in a similar way.

The role that terrestrial planets play in the evolution of the JFCs is clearly seen in the figure. The dominant dynamical effect is the obvious one—the inclusion of the terrestrial planets causes objects with small perihelion distances to slowly evolve in semi-major axis and aphelion distance. This allows some of these objects to be decoupled from Jupiter. The effect of the terrestrial planets is subtle and the comets are only slightly perturbed. We do not see, for example, a population of objects with semi-major axes near 1 AU. This is in stark contrast with the simulations in Ipatov and Mather (2003), where they find a large number of objects with semi-major axes near that of the Earth's. These authors have claimed that the reason they

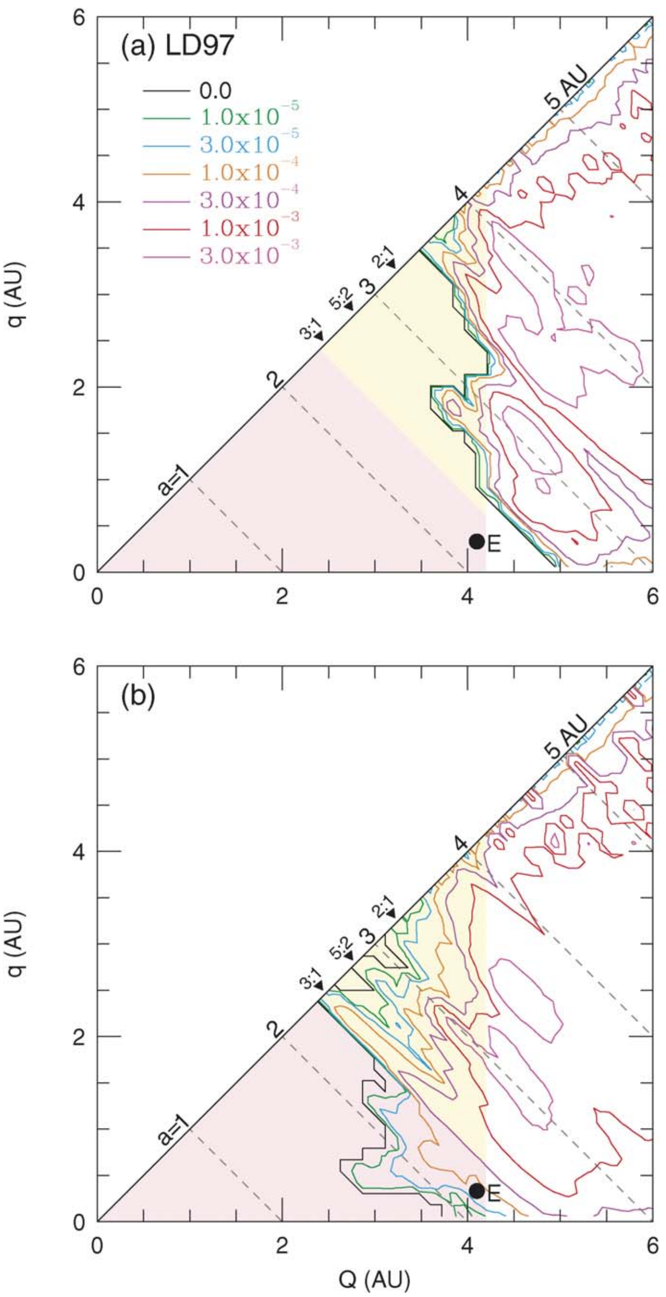

Fig. 1. Contour plots of the distribution of ecliptic comets in the inner Solar System as a function of aphelion (Q) and perihelion (q) distances. The units are the number of comets per q–Q bin, which were 0.12 AU on a side. The population is normalized so that the total number of objects with semi-major axes less than that of Jupiter (5.2 AU) and $Q < 6$ AU is equal to one. The contours are logarithmically spaced with a separation of 1/2 dex. The dashed lines are curves of constant semi-major axis (a). The triangles mark the locations of the 3:1, 5:2, and 2:1 mean motion resonances with Jupiter. The union of the two shaded regions shows the location of 'decoupled comets,' while the pink region shows where Encke-like objects ($Q < 4.2$ AU and $a < 2.4$ AU) lie. The black dot marks the orbit of 2P/Encke. (a) The distribution from LD97, which does not include the terrestrial planets. (b) The distribution from the simulations performed here which include the terrestrial planets.

see such objects and other researchers do not is that they have integrated a larger number of particles and thus they are finding rare, but important, dynamical pathways that others have missed. However, here we have integrated a similar number of particles and do not see this behavior. We believe that this discrepancy arises from the fact that Ipatov and Mather (2003) treat their planets as point masses, rather than allowing particles to hit the planets. As a result, they allow unphysically close encounters and thus unphysically large velocity kicks (δv). These large δv's are probably why Ipatov and Mather (2003) found objects with semi-major axes as small as they did.

The vast majority of our comets have semi-major axes beyond the 3:1 mean motion resonance with Jupiter. The small nudges that comets receive from the terrestrial planets do, however, allow some particles to evolve into the mean motion resonances of Jupiter, which, in turn, can further circularize their orbits. Indeed, as can been seen in Fig. 1b, the 3:1, 5:2, and 2:1 mean motion resonances can drive some objects into circular orbits.

One consequence of the fact that the terrestrial planet perturbations are weak is that very few objects become decoupled from Jupiter. If we adopt FGB02's definition that a 'decoupled comet' is one for which $Q < 4.2$ AU, we find that $\sim$0.3% of our particles meet this criterion some time during their dynamical lifetime. All of these objects evolve onto visible orbits (recall this means $q < 2.5$ AU, see Section 1). This percentage can be directly compared to the fact that 18% of our particles become visible comets.

However, not surprisingly, being removed from a Jupiter-encountering orbit significantly lengthens a particle's dynamical lifetime. If we start the clock ticking when an object first evolves onto an orbit of $q < 2.5$ AU and hence becomes visible for the first time, we find that objects that were decoupled from Jupiter had a median dynamical lifetime of 4.8×10^5 yr. This can be compared to a lifetime of 1.0×10^5 yr for objects that do not become decoupled. Again, ignoring the fact that comets can physically evolve, our model predicts that for every 10 JFCs with $q < 2.5$ AU there should be roughly one decoupled object. The steady state distribution of aphelion distances for ecliptic comets (which include both JFCs and decoupled objects) calculated by LD97 (gray histogram) and by our model (black histogram) are shown in Fig. 2. Again, the effects of the terrestrial planets can clearly be seen.

The next issue to address is whether we expect to see any 'decoupled comets' currently in the Solar System. In order to estimate this, we must first scale the distribution shown in Fig. 1b to an absolute number of comets. LD97 estimated that there are roughly 108 active JFCs with $q < 2.5$ AU and $H_T < 9$ in the Solar System, where H_T is the total absolute magnitude of an active comet. Although there probably is not a good relationship between H_T and a comet's physical radius, this corresponds to roughly 540 active comets with $q < 2.5$ AU and diameter $d > 1$ km, using the scaling in Levison et al. (2000). From Fernández et al. (1999) it can estimated that there are roughly 800 comets with nuclear magnitudes less than 18.5, which, for an albedo of 0.04, implies a diameter somewhat larger than 1 km. Given the large uncertainties in both these estimates, they are not inconsistent with each other. For the remainder of this paper, we adopt the value of 540, but the reader should understand that there is at least a factor of two uncertainty in this number.

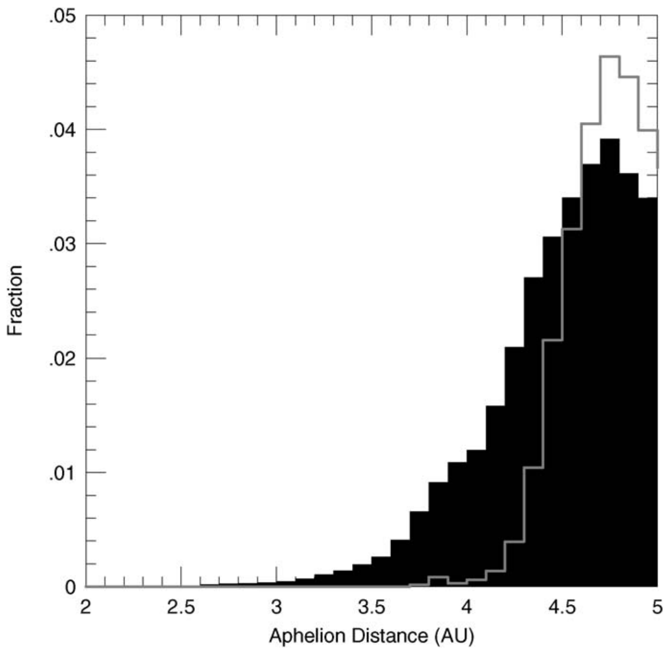

Fig. 2. The steady state aphelion distribution of ecliptic comets as predicted by LD97 (gray histogram) and our model (black histogram). Only those objects with $q < 2.5$ AU are included. In these simulations an ecliptic comet is any object with $T > 2$.

As described above, we found that for every 10 visible JFCs there should be one decoupled object. This implies that there are roughly 54 decoupled active comets with $d > 1$ km. FGB02 estimated this number to be 0.25, a factor of 200 smaller than our value. We believe that the difference is simply due to the fact that their number was based on the behavior of a single object. As we pointed out, only a small fraction of objects are decoupled. However, once they are decoupled they can be long-lived. The type of dynamical numerical experiments that are being employed to study this issue (including ours) suffer from the drawback that they can potentially miss, or underestimate, the importance of rare, but long-lived, dynamical pathways. We believe that the FGB02 results have this problem. The results presented here are based on the evolution of almost 2000 particles. So, it is much less likely that our model possesses this limitation.

So, is our model predicting that we should see 54 Enckes? This, of course, depends on what we mean by an 'Encke-like' orbit. FGB02 simply considered any object that became decoupled as Encke-like, but they could do little else because they were constrained by their small number statistics. Our simulations do not suffer from this limitation. In addition, a glance at Fig. 1b shows that this definition is probably not appropriate. The union of the two shaded regions in the figure shows where the orbits of decoupled comets lie, while the black dot shows the orbit of 2P/Encke. Note that the vast majority of our fictitious objects (recall that the contours are logarithmically spaced with a separation of $1/2$ dex) lie on orbits with significantly larger semi-major axes than 2P/Encke—orbits that lie near the major mean motion resonances with Jupiter. Indeed, according to our model, for every decoupled object with a semi-major axis interior to Jupiter's 3:1 mean motion resonance, like 2P/Encke, there should be 19 objects with larger semi-major axes. The more distant objects were mainly decoupled from Jupiter by the action of these resonances. Since 2P/Encke is outside this region, we feel that these resonant objects should not be included in our definition of 'Encke-like.' Thus, we define 'Encke-like' to mean those objects decoupled from Jupiter ($Q < 4.2$ AU) with semi-major axes interior to Jupiter's 3:1 mean motion resonance ($a < 2.4$ AU). This is the pink shaded region in the figure.

Our model is therefore predicting that there should be roughly 3 active comets in Encke-like orbits with $d > 1$ km. There is only one Encke and thus the statistics are probably consistent. We conclude that it is possible for the terrestrial planets to perturb enough objects from JFC orbits to Encke-like orbits in order to explain the fact that we see one such object.

So, are we done? Unfortunately, the answer is no. The argument presented in the last paragraph does not take into account the fact that comets physically age and become either dormant or disrupt. LD97 found that they could only match the inclination distribution of the active JFCs if these comets fade on a timescale of $\sim$12,000 yr. This number is defined as the average amount of clock time that passes between the point when a comet first evolves onto an orbit with $q < 2.5$ AU and when it becomes dormant. For our purposes here, it is perhaps better to think in terms of the number of perihelion passages rather than time. Going back to LD97's original data, we find that the 12,000 yr lifetime corresponds to roughly 400 perihelion passages with $q < 2.5$ AU. Other measures of physical lifetimes give similar values (for example, Whipple and Sekanina, 1979). Thus, if the dynamical pathway we described above were indeed the one that Encke took to reach its current orbit, then the comet must have completed its trek before it became dormant. We found that our objects undergo a minimum of 10,000 perihelion passages with $q < 2.5$ AU before they evolve onto Encke-like orbits. Indeed, on average they suffer 150,000 such passages before they can make this transition! These numbers are significantly larger than the quoted physical lifetimes of JFCs.

Fig. 3 shows the effect that accounting for physical aging has on our estimates of the number of active Encke comets. This figure was calculated in the following way. As described above, our prediction that there should be 3 active comets on Encke-like orbits is scaled to the number of active JFCs (540) and is based on the assumption that comets are active as long as they remain in the inner Solar System. However, this assumption is incorrect. LD97 estimated that the ratio of active to extinct comets is $\sim$3.5, and thus, rather than scaling the number of objects on Encke-like orbits to 540 JFCs with $d > 1$ km, we should scale it to $540 \times (1 + 3.5) = 2400$ such objects. Thus, we should expect a total of roughly 12 objects in Encke-like orbits with $d > 1$ km. This total includes both active and dormant comets and assumes that a comet becomes dormant rather than disrupting. It also does not include the effect of physical collisions between comets and asteroids. Fig. 3 shows the number of these that should be active as a function of activity lifetime.

According to these calculations, comets would need to stay active for at least 80,000 passages in order for us to expect to see a single active Encke. This value is about 200 times longer than

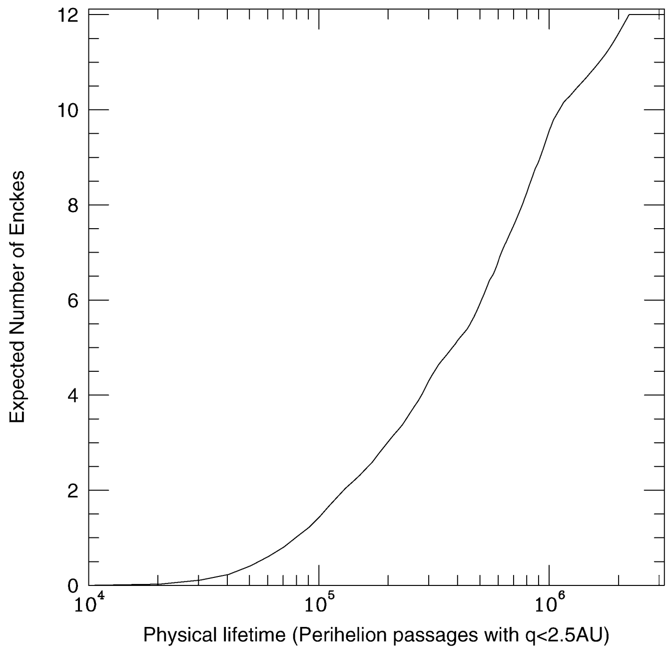

Fig. 3. Our model's prediction for the number of active comets on Encke-like orbits ($Q < 4.2$ AU and $a < 2.4$ AU) as a function of the physical lifetime of comets. LD97 found that this lifetime is roughly 400 perihelion passages with $q < 2.5$ AU.

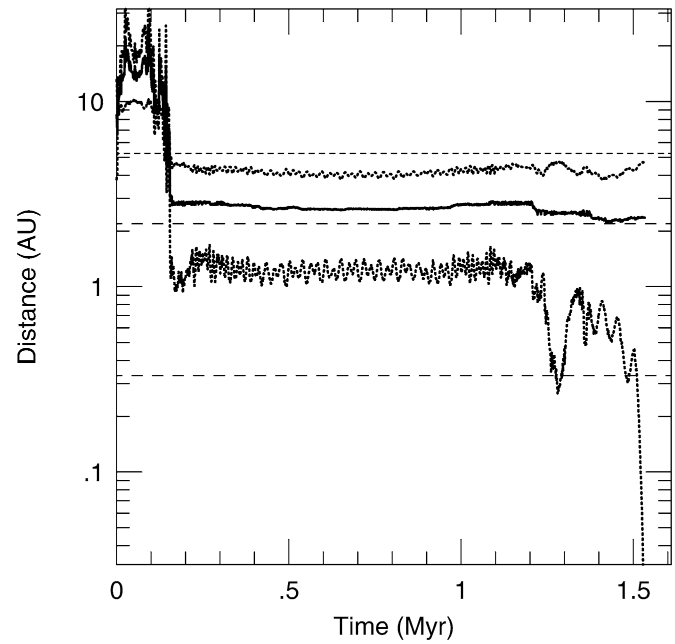

Fig. 4. The temporal evolution of a particle in our simulation that evolves onto an orbit similar to 2P/Encke's. $t = 0$ was arbitrarily chosen to be the point when the object first evolved onto an orbit with $q < 4$ AU. The solid curve shows the particle's semi-major axis, while the inner and outer dotted curves show its perihelion and aphelion distances, respectively. The short-dashed curve shows Jupiter's semi-major axis, while the inner and outer long-dashed dotted curves are 2P/Encke's current semi-major axis and perihelion distance.

published estimates of physical lifetimes! Given this result, it is tempting to argue that perhaps 2P/Encke is simply anomalously long-lived. However, there is fairly convincing argument that this is not the case. Reach et al. (2000) estimated that 2P/Encke loses between 2×10^{13} and 6×10^{13} g of material every orbit. This corresponds to change in diameter of about 0.5 m per orbit given that 2P/Encke has a diameter of 5 km (Fernández et al., 2000) and assuming a density of 1 g cm^{-3}. If the comet has remained this active for 80,000 passages, it must have originally had a diameter of ∼40 km, which is significantly larger than any known JFC (Lamy et al., 2004). Thus, 2P/Encke can be a continuously active comet only if it is unusually large and followed an unusual trajectory. We believe that this is very unlikely.

Our results seem to suggest that non-gravitational forces are required to make 2P/Encke. However, models which include these forces also face problems. FGB02's NG model suffers from the same problem that ours does, i.e., objects evolve onto Encke-like orbits but it takes too long. Pittich et al. (2004) get the correct timescale, but they employ unrealistic NG forces in order to make this happen.[1]

Thus, we are potentially faced with the conclusion that neither of the proposed dynamical pathways can produce an active comet in 2P/Encke's orbit. We believe that the most likely solution to this conundrum is that 2P/Encke went through a phase when it was dormant, but became active again perhaps by a change in its orbit. Rickman et al. (1991) showed that a comet's activity can be changed by a change in its perihelion distance. With this in mind, we suggest that 2P/Encke may have followed a dynamical evolution similar to the one shown in Fig. 4. In this figure we show the temporal evolution of the semi-major axis, perihelion distance, and aphelion distance of one of our test particles. We start to plot the particle's trajectory during a time when it is heavily interacting with both Jupiter and Saturn. At 158,000 yr (note that the time was arbitrarily set to zero at the beginning of the plot) Jupiter scatters the particle onto an orbit with $q = 1.2$ AU. Very quickly the object becomes decoupled from Jupiter, presumably due to encounters with Mars. It then evolves into the 2:5 mean motion resonance with Jupiter, which in turn, drives it into an orbit with $q \sim 1$ AU. Encounters with the Earth generate small changes in semi-major axis until, at 1.2 Myr, the object enters the ν_6 secular resonance. During the next ∼50,000 yr, the object's perihelion distance is driven inward to values of 0.31 AU (similar to 2P/Encke's). The ν_6 eventually forces the object into the Sun, a fate that will probably be shared by 2P/Encke (Levison and Duncan, 1994).

We therefore suggest that 2P/Encke first entered the inner Solar System as a normal JFC, but then became decoupled from Jupiter. It remained active for a typical amount of time and then became dormant by building up a lag deposit of inert material over its entire surface (e.g., Brin and Mendis, 1979; Prialnik and Bar-Nun, 1988). After it became dormant it continued to rattle around the inner Solar System, but kept its perihelion distance significantly larger than it is now, probably beyond 1 AU. At some point in the not too distant past, it evolved into the ν_6 secular resonance which has been driving

[1] In both these cases, however, the authors studied only a relatively small number of objects. Perhaps they are missing an unlikely, but long-lived, dynamical pathway which will solve this problem. Only future work will tell.

up its eccentricity ever since (Levison and Duncan, 1994). This sharp decrease in perihelion distance heated the comet, leading it to blow off its mantle and become active once again. We believe that this kind of scenario is the best way to explain why we see an active comet in 2P/Encke's orbit.

The physical aging of comets also solves a bothersome prediction of our model. Recall that our model predicts 19 decoupled comets with $a > 2.4$ AU for every Encke. If comets did not become dormant, this would imply a population of active comets that is not observed. However, if we repeat the exercise above for these objects, we find that comets would need to stay active for significantly longer than 11,000 perihelion passages for us to expect one such comet.

Our model, therefore, predicts (if we can believe it, given that it does not include NG forces) that there should be a significant number of decoupled dormant comets. Thus, it is natural to ask whether these objects can be contributing to the near-Earth object population and/or the main belt asteroids (MBAs). For the sake of discussion, we define the following populations. We define an NEO as a subset of decoupled objects with $q < 1.3$ AU (Shoemaker, 1983), and we define the main asteroid belt as the region where $q > 1.7$ AU, $2 < a < 3.5$ AU and eccentricity, e, less than 0.3.

According to our model, 15% of the decoupled objects are NEOs, which corresponds to a population of roughly 36 cometary NEOs with $d > 1$ km, if we scale our population to LD97's estimate of 2400 active and dormant JFCs with $q < 2.5$ AU. Note that our definition of NEO is slightly different from that employed by other works because we do not include objects with $Q > 4.2$ AU. For example, Bottke et al. (2002) estimated that there were ∼200 km-sized cometary NEOs. However, they used the LD97 integrations and thus did not have many decoupled objects. Our 36 objects should be added to theirs. These objects represent only about 20% of the approximately 1000 NEOs with $d > 1$ km. Using a similar argument, we can estimate that the main asteroid belt should contain about 100 dormant comets with $d > 1$ km, compared with roughly a million km-sized asteroids (e.g., Bottke et al., 2005, and references therein). Again, we remind the reader that these numbers assume that both NG forces and disruption (either by cometary inactivity or physical collisions) are not important for this population.

So, we find that almost all objects that appear asteroidal in orbits decoupled from Jupiter probably originated in the asteroid belt. However, asteroidal objects on Jupiter-crossing ($T < 3$) orbits are probably of cometary origin. This can be seen in Fig. 5, which shows the fraction of NEOs ($q < 1.3$ AU, $H < 18$) that are of cometary origin as a function of T. In order to generate this figure we employed the NEO model by Bottke et al. (2002). Our model predicts that almost all asteroidal objects with $T < 2$ are dormant comets, roughly 30% of these objects with $2 < T < 3$ are dormant comets, and almost all such objects $T > 3$ are from the asteroid belt. This is consistent with recent observations which show a strong transition in taxonomic type near $T = 3$ (Fernández et al., 2001, 2005; Binzel et al., 2004).

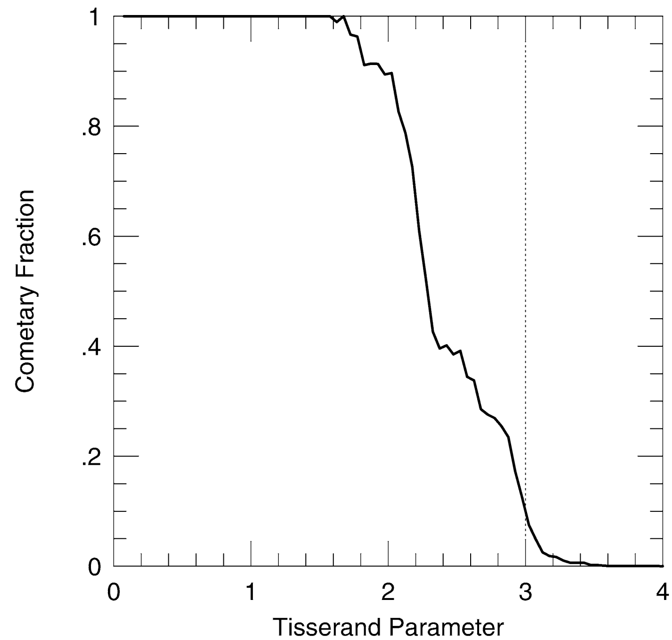

Fig. 5. Our prediction for the fraction of NEAs that are dormant comets as a function of the Tisserand parameter, T. To generate this figure we compared our comet model to Bottke et al. (2002)'s model of NEAs from the asteroid belt. $T = 3$ is marked by the dotted line. We show this fraction for objects with $H < 18$ in order to make comparisons with observations easier.

4. Conclusions

We present a series of orbital integrations designed to determine whether the orbit of Comet 2P/Encke can be the result of JFCs gravitationally scattering off the terrestrial planets. In particular, we are interested in determining whether the terrestrial planets can scatter objects onto this type of orbit (which we define as $a < 2.4$ AU and $Q < 4.2$ AU). To accomplish this, we integrated the orbits of a large number of objects from the trans-neptunian region, through the realm of the giant planets, and into the inner Solar System. The planets from Venus to Neptune were included in this simulation.

We found that only 1 out of ∼11,000 initially trans-neptunian objects will evolve onto an Encke-like orbit. At any one time, we expect there to be roughly 12 objects in this type of orbit, assuming LD97's JFC model and that comets do not disrupt. However, since it takes much longer to evolve onto an orbit like this than the typical cometary physical lifetimes, we do not expect any comet to remain active until it evolves into these orbits. Indeed, a comet must be able to survive at least 80,000 perihelion passages with $q < 2.5$ AU in order for us to expect any of these objects to be active. This is 200 times longer than published estimates of cometary lifetimes.

Our results seem to suggest that non-gravitational forces are required to make 2P/Encke. However, as we described above, models which include these forces also face problems. We believe that the most likely scenario is that 2P/Encke was dormant for much of the time it has spent in the inner Solar System and it has become active only as the ν_6 secular resonance has driven down its perihelion distance.

Our model can also be used to estimate the number of dormant comets in the near-Earth object and main belt asteroid populations. However, these estimates should be viewed with skepticism because our models do not include NG forces. With this limitation in mind, our model predicts that there are 36 cometary NEOs with $d > 1$ km and $Q < 4.2$ AU, and roughly 100 dormant comets with $d > 1$ km in the main asteroid belt.

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