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PRODUCTION OF THE EXTENDED SCATTERED DISK BY ROGUE PLANETS

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ABSTRACT

We show that if the early outer solar system contained one or more additional planets of an Earth mass or larger, these planets are likely to be temporarily emplaced in the Kuiper Belt's "scattered disk." While on an orbit of large semimajor axis, such a "rogue planet" may efficiently raise either (1) the perihelia of other scattered-disk objects, emplacing them in the "extended scattered disk," or (2) their orbital inclinations, to the levels currently observed in the Kuiper Belt. With even a single rogue planet present, the probability of producing extended scattered disk objects is 20%–50%. After the rogue is removed from the system (on a characteristic timescale of 200 Myr), most extended scattered disk orbits are not appreciably modified over the age of the solar system. Objects with large orbital inclinations like the outliers 2004 XR_{190}, 2003 UB_{313}, 2000 CR_{105}, and Sedna are also produced.

Subject headings: Kuiper Belt — solar system: formation

Online material: color figures

1. INTRODUCTION

There is increasing indirect and direct evidence that the early solar system contained a population of bodies at least Pluto-sized and almost certainly much larger. The evidence for giant impacts in general, the presence of ∼1000 km diameter trans-Neptunian objects (TNOs), and the existence of the Pluto-Charon binary (Canup 2005) all suggest that other large objects were present in the early outer solar system (Stern 1991).

Although Kuiper Belt surveys (those with more than 10 detections include Jewitt et al. 1996; Trujillo et al. 2001; Larsen et al. 2001; Gladman et al. 2001; Allen et al. 2002; Elliot et al. 2005; Petit et al. 2006; Allen et al. 2006b) are slowly building up a sample, the rarity on the sky of objects bigger than Pluto and 2003 UB_{313} indicates that many certainly remain to be discovered, especially when biases in flux and ecliptic latitude are considered. The most likely storehouse for these large objects is the Kuiper Belt's scattered disk at high inclination; the great average distance of the scattered-disk objects places many of the largest objects below the flux and angular-rate limits of even the largest-area surveys (Trujillo & Brown 2003).

The production of a spectrum of sizes during the epoch of core building is natural (see, e.g., Kenyon 2002). It is reasonable to hypothesize that in the final assembly stages there were other planetary-sized objects (Martian to Earth size or even larger) that are now departed; we call these "rogue planets" to reflect their potentially wide-ranging effects on the early Kuiper Belt. Petit et al. (1999) studied the effects of rogues on the Kuiper Belt's inner edge, but not the effect on the scattered and extended scattered disks. Morbidelli et al. (2002) concluded that an ensemble of lunar-sized or larger objects could not have formed in situ in the 30–50 AU Kuiper Belt, since they lodge themselves in low-e orbits and would have been seen by now.

Scattered-disk objects (SDOs) are TNOs with large semimajor axis orbits whose perihelion distances q are near Neptune ($q < 38$–40 AU, although definitions vary; see Gladman 2005; Emel'yanenko et al. 2003). SDOs have likely reached their current orbits after many gravitational scatterings with Neptune (Duncan & Levison 1997; Torbett 1989), but because of the scattering dynamics, they keep their perihelia close to Neptune and can only rarely (in mean motion resonances) reach higher q. The extended scattered disk objects (ESDOs) have higher perihelia (a $q > 40$ AU boundary is often used). Although some SDOs can reach high q by interaction with giant-planet resonances, the ESDO population is so large that it indicates other processes, most likely in the early solar system, are capable of raising SDO q's to produce ESDOs (Gladman et al. 2002; Morbidelli et al. 2004). Examples of such processes include close encounters with rogue planets in the disk itself (Gladman et al. 2002; Morbidelli & Levison 2004), resonant interactions (Duncan & Levison 1997; Gomes et al. 2005), and passing stars (Ida et al. 2000; Kenyon & Bromley 2004; Morbidelli & Levison 2004; Kobayashi et al. 2005).

This Letter presents a preliminary exploration of scenarios in which rogue planets are temporarily present in the scattered disk and sculpt the TNO orbital distribution. The parameter space is large, but we show the physical mechanism to be efficient and plausible.

2. NUMERICAL SIMULATIONS

The majority of our simulations used the Mercury 6 integrator package (Chambers 1999), following the orbital evolution of four giant planets, one or more rogue planets of smaller mass, and a set of test particles. To confirm reproducibility, we duplicated many simulations using the SyMBA integrator (Duncan et al. 1998); we never found a statistically meaningful difference between the results of the two integrators.

We began with three sets of 30 simulations, sharing an initial state of four giant planets with their current orbits and 300 test particles uniformly placed between $a_0 = 20$ AU and $a_0 = 50$ AU ($e = 0.01$, $i_0 = 1°$ always). Orbital elements are barycentric, with i relative to the invariable plane. Objects were eliminated if their heliocentric distances exceeded 1500 AU (where the Galactic tidal field and effects of passing stars become nonnegligible). In the first set, 10 Martian-mass rogues with $q_0 = 30$ AU were placed at 1 AU intervals between $a_0 = 31$ AU and $a_0 = 40$ AU. In the second set, an Earth-mass planet with $a_0 = 35$ AU and $q_0 = 30$ AU ($i_0 = 1°$) was added to the 10 Martian-mass embryos (very roughly a D^{-4} size distribution). In the third set, only the Earth-mass rogue was present. The 30 simulations within each set were identical except for the randomized argument of pericenter, nodal longitude, and mean anomaly of the rogue(s). The three sets were integrated

TABLE 1
PROBABILITY OF PRODUCING AN EXTENDED SCATTERED DISK

m_r ($M_\oplus$)	TIME[a] (Myr)	N_{sim}	FRACTION WITH SMALL BODIES WITH $a > 100$ AU AND $q > 40$ AU	$q > 42$ AU	$q > 45$ AU	$q > 50$ AU
1	100	47	10.6	6.4	2.1	2.1
	200[b]	47	34.0	31.9	29.8	27.7
2	100	33	78.8	45.5	33.3	24.2
	200[c]	61	47.5	44.3	34.4	32.8
2+2[d]	200	94	96.8	71.3	46.8	26.6

[a] Duration of simulations.
[b] The 1 $M_\oplus$ simulations for which the rogue survived more than 100 Myr.
[c] The 2 $M_\oplus$ simulations for which the rogue survived more than 100 Myr.
[d] A 2 $M_\oplus$ rogue with 2 $M_\oplus$ disk. All simulations ran 200 Myr.

for 300, 500, and 100 Myr (respectively), and frequent test-particle perhihelion lifting ($q > 40$ AU) was observed when an Earth-mass rogue was present. Petit et al. (1999) observed that dynamical excitation was dominated by the most massive objects (although we see below that close encounters are minor here). Martian-mass rogues were thus removed from subsequent simulations, and the effect of changing the mass of the remaining rogue was tested in sets of 10^8 yr simulations with a rogue with mass m_r of one-quarter, one-half, the same, twice, or 4 times that of Earth. Our studies show that ESDO emplacement occurs only once $m_r \geq 1\ M_\oplus$. We thus increased both the timescale and number of test particles to quantify the effect.

Our main results are based on sets of 94 simulations with a rogue of mass $m_r = 1\ M_\oplus$ or $m_r = 2\ M_\oplus$ with initial $a_0 =$ 35 AU, $q_0 = 30$ AU, and 900 test particles uniformly from $a_0 = 20$ to $a_0 = 50$ AU. The initial conditions were identical except for the rogue's three remaining orbital angles. Because significant modification of surviving ESDO orbits are not expected after the rogue is expelled, only simulations in which the rogue survived 100 Myr were extended to 200 Myr, and in a few cases to 1 Gyr if the rogue was still present. As before, significant perihelion lifting was commonly observed; the next section discusses the details. In particular, the final distribution of q and i is at times strikingly similar to our currently known Kuiper Belt. To confirm that this result was not sensitive to the rogue's initial location, 94 simulations with $m_r = 1\ M_\oplus$, $a_0 = 25$ AU, and aphelion at 30 AU were performed; the results were statistically similar to the $q_0 = 30$ AU case. This is not surprising, since the initial speed of the rogue relative to Neptune (similar in these two cases) would be the important factor. Finally, to investigate if a massive disk would force a more rapid elimination of the rogue planet, we performed 93 more $m_r = 2\ M_\oplus$ simulations in which the total mass of 900 identical small bodies was equal to 2 $M_\oplus$.

3. RESULTS

Table 1 presents the fraction of the simulations that produced extended scattered disks. Note that for massless test particle cases, only simulations in which the rogue lived 100 Myr were extended to 200 Myr. Since the low-q boundary of ESDOs is not well defined in the literature, and because the production of $a < 100$ AU ESDOs might be due to other mechanisms, Table 1 gives the fraction of the simulations that produced $a > 100$ AU ESDOs with perihelia above several different limits. Considering all the simulations, the half-life for the rogue planet is ~200 Myr (i.e., it essentially behaves as a test particle). For $m_r = 1\ M_\oplus$, ESDOs are only rarely created unless the rogue lives longer than 100 Myr; however, high-q bodies are created one-quarter to three-quarters of the time (depending on how stringent a q-threshold is used). We find that the presence of a small-body disk with mass equal to the 2 $M_\oplus$ rogue only marginally shortens the half-life of the rogue (160 Myr instead of 200 Myr), while making ESDO production somewhat more common.

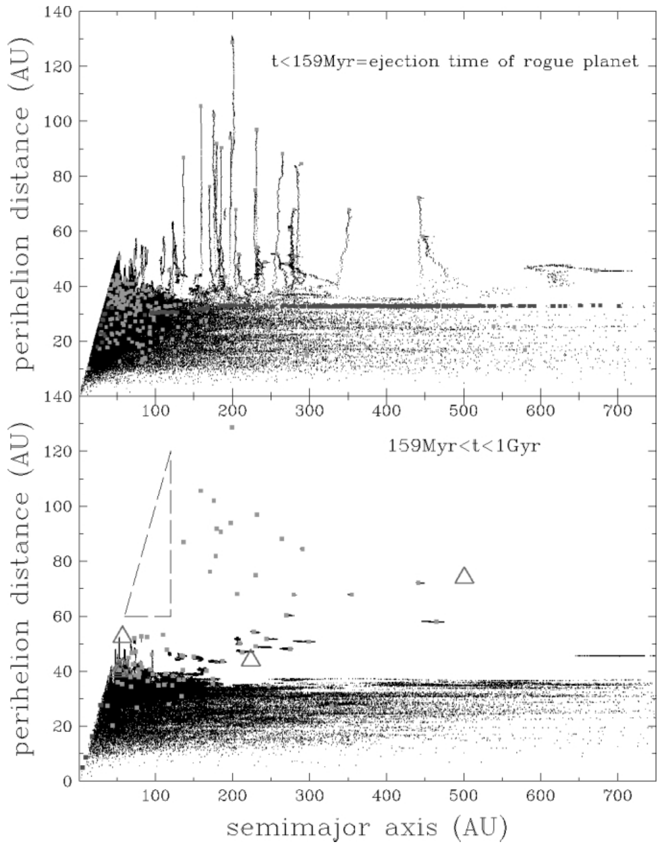

FIG. 1.—Evolution of the outer solar system in one of our simulations. A 2 $M_\oplus$ rogue began with $a = 35$ AU and $q = 30$ AU. *Top*: During the first 159 Myr of evolution (until the rogue is ejected), its a vs. q evolution is shown by the dark gray squares. Any (a, q)-points visited by test particles receive black dots, and light gray squares give orbital elements at 159 Myr for surviving particles. The paths of some small bodies to high q are easily seen. *Bottom*: After the rogue is ejected, the scattered disk continues to erode, but the ESDOs cease to evolve. The orbits of five known ESDOs are shown. The absence of objects with $q > 60$ and $a < 120$ AU is highlighted by the dashed triangle. [*See the electronic edition of the Journal for a color version of this figure*.]

Figure 1 shows two portions of the time evolution of a system in which a 2 $M_\oplus$ rogue survives 159 Myr before ejection. The rogue was quickly scattered to $a > 200$ AU in ~20 Myr and lives in the scattered disk with $q \simeq 34$ AU for another 140 Myr (Fig. 2). Very dramatic small-body perihelion-raising events are visible in Figure 1, where SDOs obtain $q > 40$ AU and, in some cases, $q > 80$ AU. Although the roughly constant a of the bodies might be thought to point to mean motion resonances with the rogue, Figure 2 shows that the rogue's a is highly variable during the q-raising period of different particles. In fact, the e-oscillation is a secular perturbation due to the rogue's presence.

Because the rogue's a varies and its orbit crosses those of the small bodies, we can only obtain order-of-magnitude dynamical timescale estimates. The secular oscillation period P_{sec} of a small body with semimajor axis a can be expressed

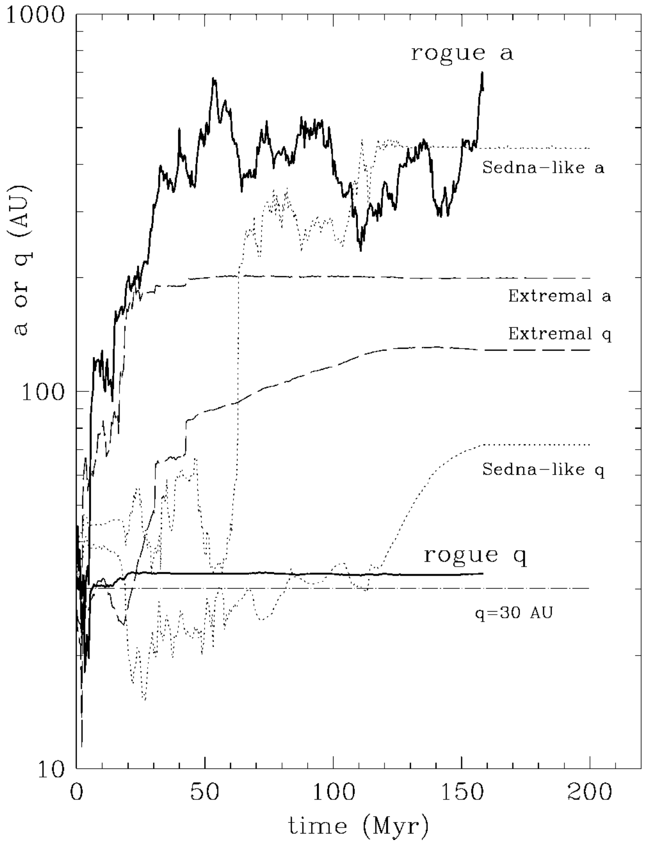

FIG. 2.—Time evolution of a and q for Fig. 1's rogue simulation. In a few million years the rogue is scattered to $a > 100$ AU and remains with q just above 30 AU for another ∼150 Myr (i.e., it lives in the scattered disk). Two test-particle histories are also shown; their perihelia are raised out of the scattered disk into the extended scattered disk through secular perturbations from the rogue planet. Once the rogue is ejected from the solar system (at 159 Myr) the ESDOs stop evolving.

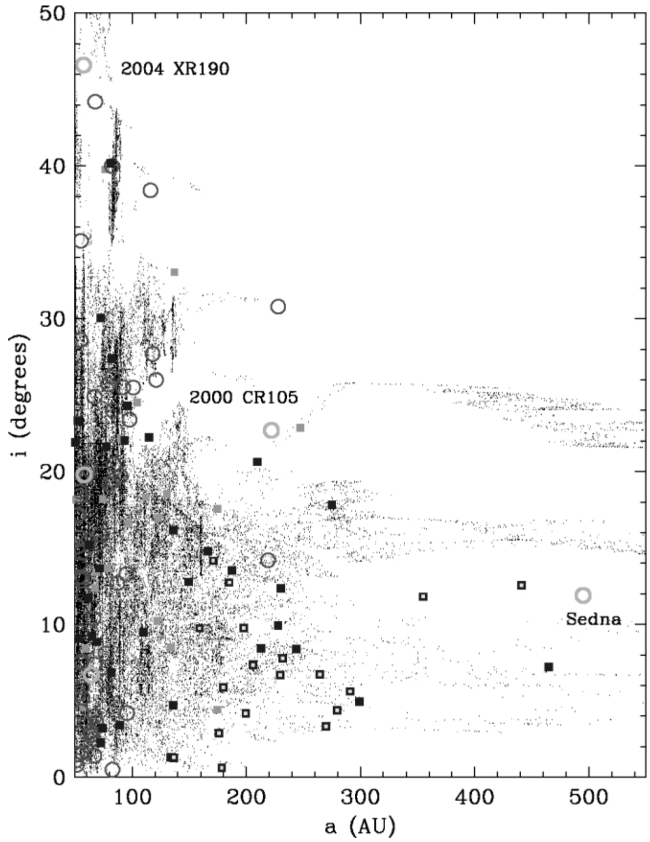

FIG. 3.—Orbital inclinations for Fig. 1's simulation during the first 10^9 yr. Dots show (a, i)-pairs visited by SDOs with $q < 40$ AU; black circles show known SDOs (note that there is a strong detection bias favoring low i). Gray and black squares respectively show (a, i) at 1 Gyr for $q < 40$ AU and $q > 40$ AU simulated objects; the gray squares will thus disappear during subsequent erosion, populating the scattered-disk field. The black squares denote simulated ESDOs (harder to detect than SDOs); those with light centerrs have $q > 50$ AU, and their absence (excepting 2000 CR_{105}, Sedna, 2004 XR_{190}, and a few other real $q > 40$ AU objects, denoted by thick gray circles) may be an observational selection effect. [*See the electronic edition of the Journal for a color version of this figure*.]

as a multiple of the rogue's orbital period P_r and its orbital a_r and e_r as

$$\frac{P_{\rm sec}}{P_r} \sim \left(\frac{M_\odot}{m_r}\right)\left(\frac{a_r}{a}\right)^{3/2}(1-e_r^2)^{3/2}, \qquad (1)$$

where $M_\odot$ and m_r are the Sun's and planet's mass and $a < a_r$. This expression makes our earlier results and the features of Figure 1 clearer. The ∼150 Myr half-life of the rogues sets a natural timescale for the problem. If there are a large number of rogues with small masses, the secular timescale for their perturbations becomes too long—hence the absence of perihelion lifting when $m_r < 1\ M_\oplus$, regardless of the number of rogues (this presumably explains why Morbidelli & Levison [2004] did not observe the behavior in simulations where the largest rogues had 0.5 $M_\oplus$). For $a_r \simeq$ 200–500 AU and $e_r \simeq$ 0.85–0.95 (giving $q \simeq 35$ AU), $P_{\rm sec}$ for $a =$ 200–400 AU varies from ∼50 to 300 Myr. The oscillation period for large-a particles is about twice the lifetime of the rogue for the case of Figure 1, explaining why large-a particles typically have time to complete only half a secular cycle (reaching minimum eccentricity) before the rogue disappears. In addition, for $a \ll a_r$ the oscillation timescale again becomes longer than typical rogue lifetimes. This could explain the absence of ESDOs with $a < 100$ AU and $q > 50$ AU (which Morbidelli & Levison [2004] used as a constraint). Although we are unsure how strong this constraint is observationally, especially with the recent discovery of 2004 XR_{190} (Allen et al. 2006a), the rogue-planet model can indeed lift q preferentially for distant objects without modifying the $a < 100$ AU region substantially.

In this model, ESDOs have a and e randomly set by what a they happened to have when they were lifted out of the scattered disk, starting at an epoch of $q \simeq$ 34–38 AU (when they are only weakly coupled to Neptune by gravitational encounters, and secular perturbations have time to raise q). The model is thus more flexible than those that rely on perturbations related to mean motion resonances (e.g., Gomes et al. 2005), since those models are confined to lifting at resonant a. Figures 1 and 2 show that once perihelion lifting begins, close encounters between small bodies and the rogue are uncommon (because of the immense trans-Neptunian volume).

Although rogues in our simulations rarely achieve $i > 10°$, the small bodies often do. Figure 3 shows the inclination behavior for the simulation of Figure 1, which possesses the characteristic (generically produced in our simulations) of an extended scattered disk in which the maximum inclinations $i_{\max}$ produced are a declining function of a; a rough envelope from our 2 $M_\oplus$ simulations is $i_{\max} = 70° \times (100\ {\rm AU}/a)$. This is in contrast to stellar-passage models, which generically produce larger i_{max} for increasing small-body a (Ida et al. 2000; Kenyon & Bromley 2004; Kobayashi et al. 2005). We have conducted another set of simulations with the rogue having $i_0 = 10°$ and find that this signature remains generic, although slightly higher ESDO inclinations occur.

In the case of a residual disk with mass equal to that of the rogue, we find that this disk does not fundamentally alter the dynamics. Both the rogue and the majority of the small bodies are again lofted into the scattered disk. Unlike situations in which an embryo is scattered into a cold disk (e.g., Brunini & Melita 2002), the rogue is unable to gravitationally decouple from Neptune by giving its angular momentum to the small bodies, since the small-body population in which it is immersed already has high e. The half-life of rogues is about 200 Myr, and ESDOs are still efficiently created (Table 1).

4. DISCUSSION AND FUTURE WORK

The rogue planet leaves behind a regular (Neptune-coupled) and an extended scattered disk. Although the ESDOs are stable after the rogue disappears, the scattered disk will erode to ~1% of the population left at the time of the rogue's disappearance (Duncan & Levison 1997). In Figure 1, the ESDO-to-SDO ratio is of order unity when the rogue disappears; ESDOs would be 100 times more numerous than SDOs at the present epoch. This ratio is in line with that estimated in Gladman et al. (2002) based on the existence of 2000 CR_{105}. Brown et al. (2004) estimate a considerably larger ESDO population based on an isotropic distribution; if the large-a population is confined to ecliptic latitudes of less than 15° (Fig. 3), then the population ratio is also ~100.

The rogue and stellar-passage scenarios each have strengths and weaknesses for ESDO production. Stellar flybys require a relatively fine-tuned passage in stellar orbital i and q in order to produce the observed ESDOs without producing low-e ESDOs or "wiping out" the Kuiper Belt (by raising its velocity dispersion and shutting down accretion). The probability of producing a Kuiper Belt like that observed seems rather small (although this might arguably be anthropic reasoning). Stellar scenarios also suffer from a potentially worrying "timing argument" in which the star must not come by too early (in which case there are no large objects around to scatter, because the giants have not created the scattered disk yet, or potentially preventing ≥1000 km objects from forming at all), and yet it cannot happen too late, since then either the probability of a close stellar passage drops as time goes by and the Sun's birth cluster dissolves, or the solar system's Oort Cloud (Levison et al. 2004) will be stripped off. However, this scenario is easily capable of lifting a large population of $a > 100$ AU SDOs to large i and q.

In the rogue scenario, timing is more "natural" in the sense that a rogue will not form until large numbers of Pluto-scale objects have already formed. The rogue then creates ESDOs on the timescale of the rogue's dynamical lifetime in the scattered disk; this requires no tuning of timescales or initial conditions. However, the rogue (in the simulations presented in this Letter) must be scattered to large a rapidly to prevent emptying the classical Kuiper Belt. In addition, the rogue scenario has the same problem as other theories in not addressing the reason that the solar system may require a sharp outer edge in the primordial disk to prevent rampant outward migration of the giant planets (Gomes et al. 2004).

There are many possible variants of the rogue scenario. There is nothing sacred about the location of Neptune or the timing of ESDO production. For example, the rogue could be emplaced and interact with a scattered disk created by another giant in an earlier phase; it would still be capable of lifting objects to $q > 40$ AU. A multi-Earth–mass rogue could have been created in an early "compact" outer solar system (Thommes et al. 1999) and still have so little mass that Jupiter and Saturn would scatter it out into a $q \sim 10$ AU scattered disk along with the other smaller planetesimals in the intergiant region. A Neptune that migrated later would then never have had gravitational access to the $q > 40$ AU ESDOs emplaced in an earlier phase.

The Kuiper Belt's high-i population is the discriminating lever arm for the rogue-planet scenarios (especially relative to the passing-star scenarios). If the currently observed trend continues (admittedly based on sparse statistics) of maximum inclinations that drop for ESDO groups with increasing a (going from ~45° for 2004 XR_{190} and 2003 UB_{313} to 23° for 2000 CR_{105} and to 12° for Sedna), then only extremely finely tuned stellar-passage scenarios will be tenable. A rogue in our solar system would have likely produced abundant high-i, $q > 50$ AU ESDOs with $a = 60$–300 AU, which remain to be discovered.

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