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# SCENARIOS FOR THE ORIGIN OF THE ORBITS OF THE TRANS-NEPTUNIAN OBJECTS 2000 $CR_{105}$ AND 2003 $VB_{12}$ (SEDNA)

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## ABSTRACT

Explaining the origin of the orbits of 2000 $CR_{105}$ ($a = 230$ AU, $q = 44$ AU) and 2003 $VB_{12}$ ($a = 531$ AU, $q = 74$ AU, unofficially known as Sedna) is a major test for our understanding of the primordial evolution of the outer solar system. Gladman et al. have shown that 2000 $CR_{105}$ could not have been a normal member of the scattered disk that had its perihelion distance increased by chaotic diffusion. The same conclusion also clearly applies to 2003 $VB_{12}$. In this paper, we explore five seemingly promising mechanisms to explain the origin of the orbits of these peculiar objects: (1) the passage of Neptune through a high-eccentricity phase, (2) the past existence of massive planetary embryos in the Kuiper belt or the scattered disk, (3) the presence of a massive trans-Neptunian disk at early epochs that perturbed highly inclined scattered-disk objects, (4) encounters with other stars that perturbed the orbits of some of the solar system's trans-Neptunian planetesimals, and (5) the capture of extrasolar planetesimals from low-mass stars or brown dwarfs encountering the Sun. Of all these mechanisms, the ones giving the most satisfactory results are those related to the passage of stars (4 and 5). An important advantage of both stellar-passage scenarios is that all the resulting objects with large perihelion distances also have large semimajor axes. This is in good agreement with the fact that 2000 $CR_{105}$ and 2003 $VB_{12}$ have semimajor axes larger than 200 AU and no other bodies with similar perihelion distances but smaller semimajor axes have yet been discovered. We favor mechanism 4, since it produces an orbital element distribution that is more consistent with the observations, unless 2000 $CR_{105}$ and 2003 $VB_{12}$ represent a population more massive than a few tenths of an Earth mass, in which case this mechanism is not viable.

*Key words:* celestial mechanics — Kuiper belt — minor planets, asteroids — planets and satellites: formation — solar system: formation

## 1. INTRODUCTION

The trans-Neptunian population of small bodies is usually divided into two categories, the Kuiper belt and the scattered disk, although the partition between the two is not precisely defined. In Morbidelli et al. (2003), we introduced a partitioning based on the dynamics of orbits in the current solar system. We called the *scattered disk* the region of the orbital space that can be visited by bodies that have encountered Neptune within a Hill radius at least once during the age of the solar system, assuming no substantial modification of the planetary orbits. We then called the *Kuiper belt* the complement of the scattered disk in the $a > 30$ AU region.

The bodies that belong to the scattered disk in this classification scheme do not provide us with any significant clue about the primordial architecture of the solar system. This is because their current orbits could be achieved by purely dynamical evolution in the current planetary system. The opposite is true for the orbits of the Kuiper belt objects. All bodies in the solar system must have been formed on orbits typical of an accretion disk (e.g., with very small eccentricities and inclinations). Therefore, the fact that most Kuiper belt objects have a non-negligible eccentricity, inclination, or both reveals that some excitation mechanism, which is no longer at work, was active in the past (Stern 1996).

In this respect, particularly interesting are those bodies with large semimajor axes ($a > 50$ AU) and large perihelion distances ($q \gtrsim 40$ AU), such as 2001 $QW_{297}$ ($a = 51.3$ AU, $q = 39.5$ AU, $i = 17\overset{\circ}{.}1$), 2000 $YW_{134}$ ($a = 58.4$ AU, $q = 41.2$ AU, $i = 19\overset{\circ}{.}8$), 1995 $TL_8$ ($a = 52.5$ AU, $q = 40.2$ AU, $i = 0\overset{\circ}{.}2$), 2000 $CR_{105}$ ($a = 230$ AU, $q = 44.4$ AU, $i = 22\overset{\circ}{.}7$), and, most recently discovered, 2003 $VB_{12}$ ($a = 531$ AU, $q = 74.4$ AU, $i = 11\overset{\circ}{.}9$; Brown et al. 2004). We call these objects *extended scattered disk* objects because they are on orbits with semimajor axes similar to other scattered-disk objects but their perihelion distances are outside (or "extended" beyond) the range for the normal scattered disk (Duncan & Levison 1997; Gladman et al. 2002; Emel'yanenko et al. 2003; Morbidelli et al. 2004). Their large eccentricities strongly suggest that they were gravitationally scattered onto their current orbits. However, this cannot have been done by the current planetary system.

Perhaps that most promising idea for the formation[1] of these extended scattered disk objects (or at least most of them) was recently studied by Gomes (2003a), who investigated whether the scenario proposed in Gomes (2003b) for the origin of the dynamical structure of the "hot Kuiper belt population" (the population of nonresonant bodies with large inclinations)

[1] A note on semantics: This paper is about the formation or origin of the dynamically excited orbits of objects in the trans-Neptunian region. So, when we discuss the "formation" or "origin" of an object, we are referring to the dynamical process by which it obtained its orbit, not about how it accreted.

could also be responsible for the extended scattered disk. We remind the reader that in Gomes's (2003b) scenario, the hot population was originally part of the primordial, massive scattered disk population. During Neptune's migration, a small fraction of these objects had their perihelion distances increased, and thus they became permanently trapped on stable orbits. Gomes (2003a) found several particles with $a > 50$ AU that increased perihelion distance well beyond 40 AU.

However, in all cases the large-$q$ objects produced in Gomes's simulation have semimajor axes smaller than 200 AU, which suggests that this mechanism is unlikely to be responsible for placing 2000 $CR_{105}$ onto its current orbit. Indeed, 2000 $CR_{105}$ is special for a couple of reasons. Until the recent discovery of 2003 $VB_{12}$, it had the largest semimajor axis in the extended scattered disk, by a large margin. It also had a significantly larger perihelion distance than any other extended scattered disk object. Although it is possible that 2000 $CR_{105}$ is just an outlying member of the extended scattered disk, the fact that no objects with perihelion distance comparable to that of 2000 $CR_{105}$ but with a smaller $a$ had been discovered seems significant to us. This is particularly true considering that observational biases sharply favor the discovery of objects with smaller semimajor axes. Thus, we were motivated to look for dynamical mechanisms that preferentially raised the perihelion distance of scattered-disk objects at large semimajor axis. The discovery of 2003 $VB_{12}$ came a few days before the submission of this paper and supported our original motivation. We stress that the orbit of this new body definitely falls beyond the distribution produced in Gomes's model.

Some of the mechanisms investigated in this paper have already been suggested, but they have never been quantitatively explored. In § 2, we consider the case in which Neptune was more eccentric in the past, as proposed by Thommes et al. (1999). It is obvious that a more eccentric Neptune would produce an extended scattered disk, but it is not known, a priori, what eccentricity would be required to produce objects on 2000 $CR_{105}$–like orbits, and over what timescale. In § 3, we investigate the effects of the presence of terrestrial-mass planet(s) in the Kuiper belt or in the scattered disk, as proposed by Morbidelli & Valsecchi (1997) and Brunini & Melita (2002). In § 4, we propose a new model for the origin of 2000 $CR_{105}$ in which the Kozai-like perturbations raised by a massive disk beyond ~70 AU increased the perihelion distance of highly inclined scattered-disk objects. In § 5, we investigate the scenario of a stellar passage perturbing the trans-Neptunian population and, particularly, the scattered disk. This scenario was first proposed by Ida et al. (2000; see also Stern 1990 for a pioneering investigation) to explain the structure of the inner Kuiper belt. Although we disagree that all the sculpting of the Kuiper belt could be due this mechanism (see Levison et al. 2004), it is still possible that a more gentle encounter could have formed objects such as 2000 $CR_{105}$ and 2003 $VB_{12}$. Finally, in § 6 we discuss a novel scenario in which 2003 $VB_{12}$ and, possibly, 2000 $CR_{105}$ are extrasolar planetesimals captured from a low-mass star or a brown dwarf during a close encounter with the Sun.

## 2. ECCENTRIC NEPTUNE

It is possible that at some time in the early epochs of the solar system, Neptune was on an orbit that was significantly more eccentric than its current one. A high eccentricity could have been achieved during a phase when the planet experienced encounters with Jupiter and Saturn, as proposed by Thommes et al. (1999). It could also be the result of interactions between Neptune and other hypothetical massive planetary embryos or of its temporary capture in a resonance with one of the other planets, although these scenarios have never been quantitatively simulated. In this section we investigate the effects that an eccentric Neptune would have on the formation of the scattered disk.

Our numerical experiment is very simple. We have performed a series of 1 Gyr integrations of the evolution of 1000 test particles, initially placed on circular and coplanar orbits between 30 and 50 AU. The runs differ from one another in the eccentricity of Neptune, which was set to either 0.1, 0.2, 0.3, or 0.4. All the other initial orbital elements of the planets were chosen to be equal to their current values. However, Uranus was removed in the integrations where Neptune's eccentricity was equal to 0.3 or 0.4, to avoid close encounters between the planets. The integrations have been performed using the RMVS3 integrator in the SWIFT package (Levison & Duncan 1994) with a global time step of 1 yr.

To visualize the extent of the scattered disk produced in the above simulations, we have divided the ($a$, $q$)-plane into cells and computed the cumulative time spent by each test particle in each cell. The results are illustrated in Figure 1, using a gray scale in which a darker color corresponds to a shorter residence time. The white areas show the regions that were not visited by any test particle during the entire integration time. The circled gray dots denote the current positions of 1995 $TL_8$ and 2000 $CR_{105}$, prominent representatives of the extended scattered disk. As one can see, while objects on orbits similar to 1995 $TL_8$ are easily produced by a Neptune on an orbit with $e = 0.1$ (but not if Neptune is on its current orbit; Duncan & Levison 1997), objects on orbits like that of 2000 $CR_{105}$ require that Neptune's eccentricity be at least 0.4. Objects with orbits similar to 2003 $VB_{12}$ are not produced even in this extreme case.

Although it is possible that Neptune once had an eccentricity as large as 0.4 (see Thommes et al. 1999), we doubt that this scenario can explain the origin of 2000 $CR_{105}$'s orbit, for two reasons. First, this scenario predicts many more bodies with 50 AU $< a <$ 90 AU than with 200 AU $< a <$ 240 AU, for 40 AU $< q <$ 45 AU. This can be seen in Figure 1$d$, which shows that the total time spent in the former region is much larger than in the latter. This result is exacerbated by the observational biases, which would strongly favor the discovery of the bodies with the smallest semimajor axes.

The second, even more compelling, reason is that in our simple integrations it takes 92 Myr before that the first body reaches $a > 220$ AU and $q > 44$ AU (it takes 24 Myr to reach $a > 220$ AU without a restriction on $q$). However, in reality it is not possible for Neptune's eccentricity to have remained this large for so long. In a more realistic situation, Neptune's eccentricity is damped very rapidly (less than a million years) by the dynamical friction exerted by the planetesimal disk (Thommes et al. 1999). In fact, in none of the Thommes et al. integrations was a body on a 2000 $CR_{105}$–like orbit ever produced (E. Thommes 2003, private communication).

It should be noted that our simulations did leave out some physical processes that may have been important at this time in the solar system's evolution—namely, collective gravitational effects and collisions among the disk particles. However, we think that the inclusion of these processes is unlikely to aid in the production of objects such as 2000 $CR_{105}$ and 2002 $VB_{12}$. On the contrary, we believe that including them would make matters worse. Collective effects, which reduce the overall excitation of the disk, would presumably damp

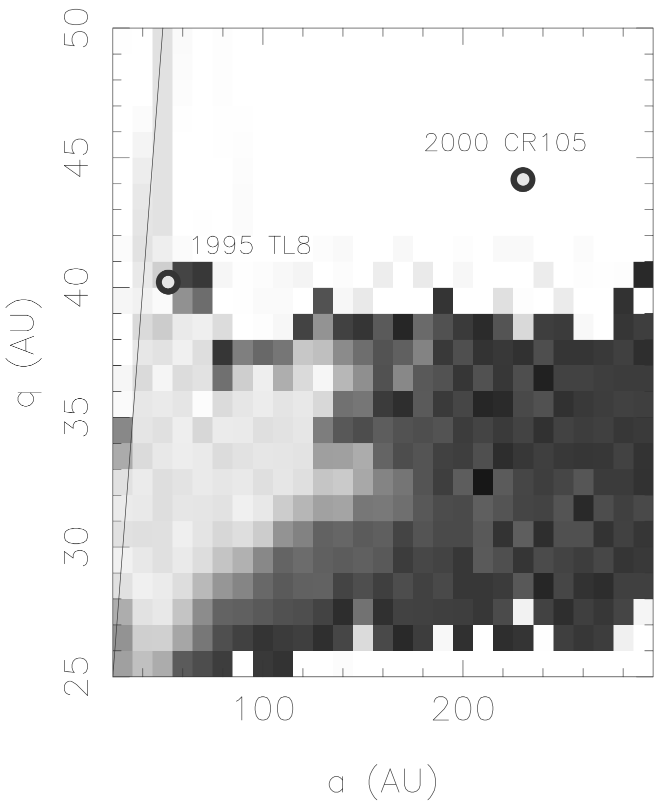


FIG. 1*a*

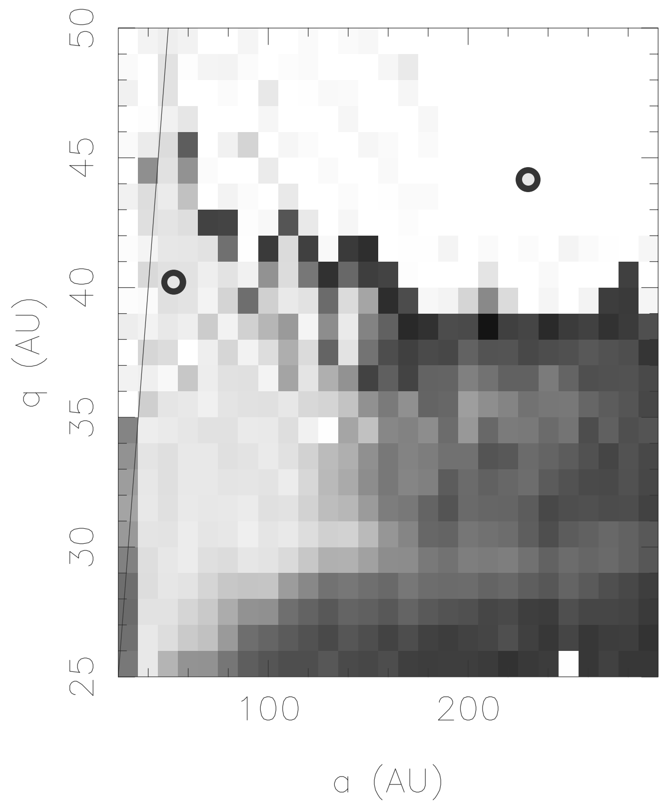


FIG. 1*b*

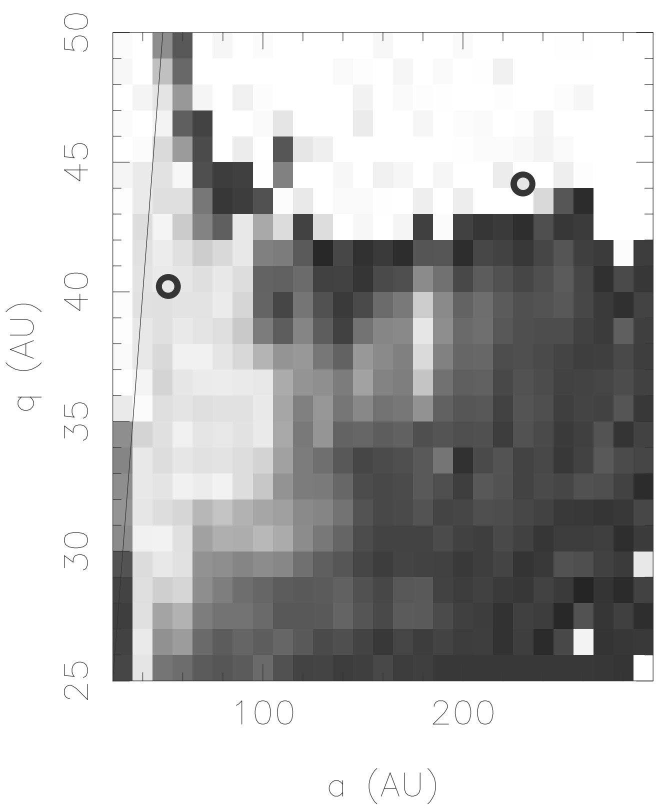


FIG. 1*c*

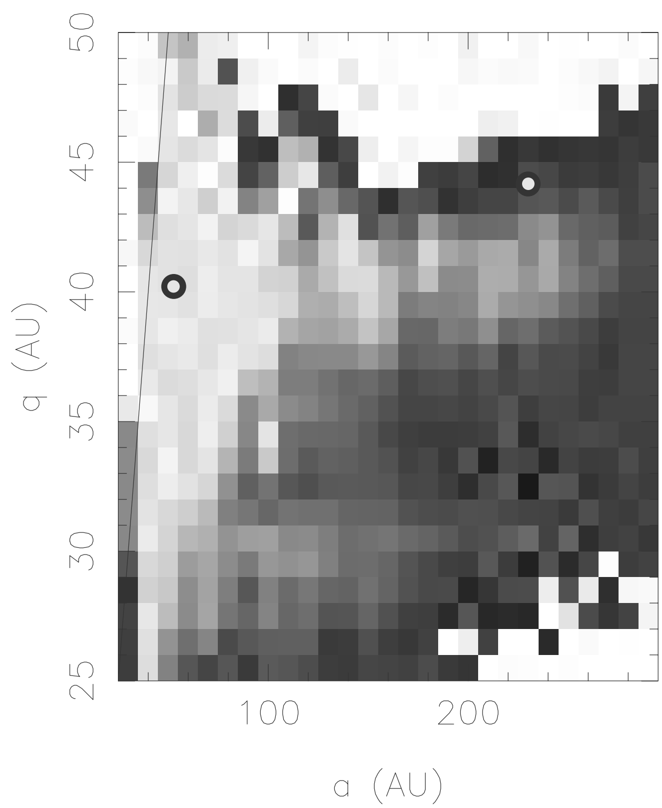


FIG. 1*d*

FIG. 1.—Extent of the scattered disk that is generated by a Neptune on increasingly eccentric orbits: (*a*) $e = 0.1$, (*b*) $e = 0.2$, (*c*) $e = 0.3$, (*d*) $e = 0.4$. The gray scale denotes the cumulative time spent by the integrated test particles in the $10 \times 2$ AU cells of the ($a$, $q$)-plane. A darker color denotes a shorter time. The uncolored region was never visited by a test particle during the 1 Gyr integration. The circled gray dots denote the positions of 1995 $TL_8$ ($a = 52.69$ AU, $q = 40.2$ AU) and 2000 $CR_{105}$ ($a = 230$ AU, $q = 44.2$ AU).

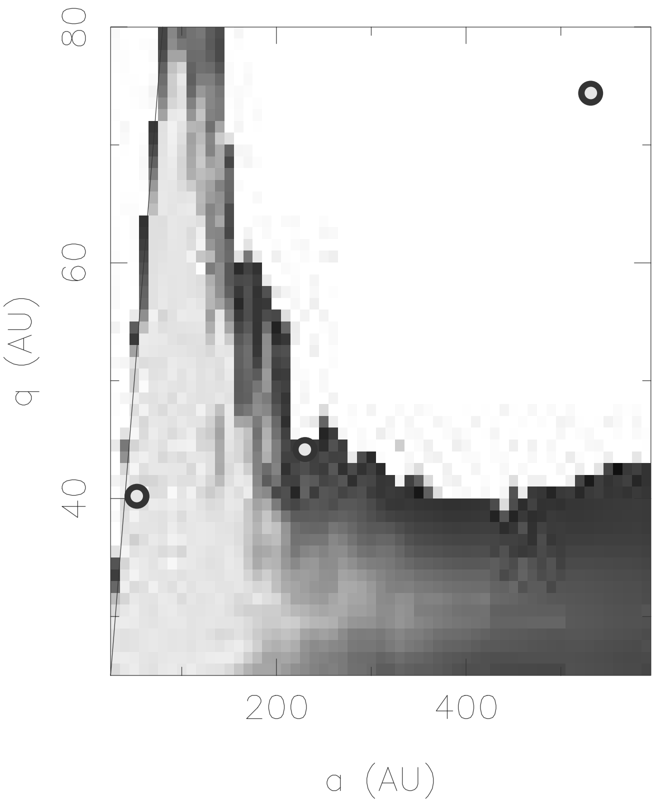


FIG. 2*a*

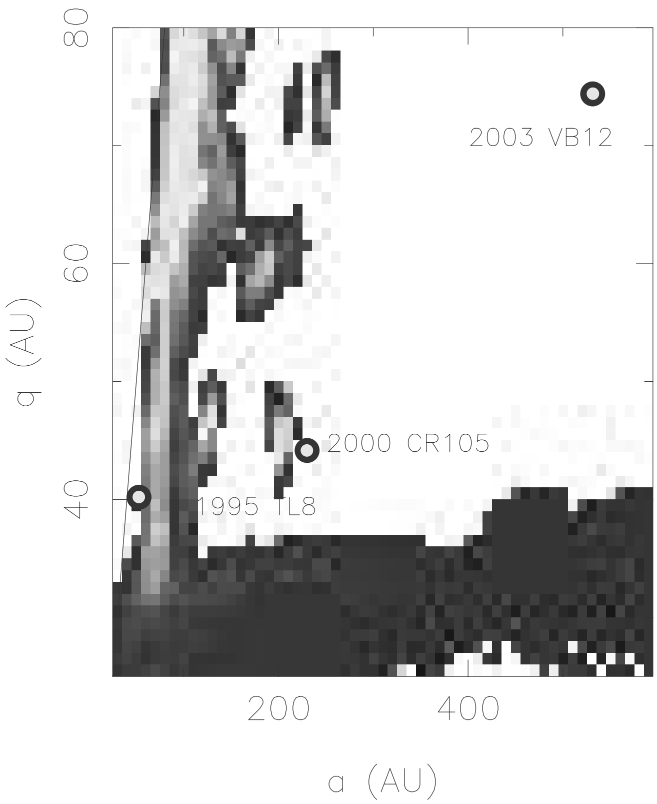


FIG. 2*b*

FIG. 2.—(*a*) Region of the (*a*, *q*)-plane visited by test particles evolving under the influence of the four giant planets and 10 half–Earth-mass embryos. The embryos were initially between Uranus and Neptune and all eventually evolved into the scattered disk. The gray scale representation is analogous to that of Fig. 1. (*b*) Same as (*a*), but for particles initially between 42 and 75 AU, under the influence of the four giant planets and of an Earth-mass planet at $a = 62.83$ AU, $e = 0.2$, and $i = 6^{\circ}$. The dot in the upper right corner of each panel represents 2003 $VB_{12}$.

Neptune's eccentricity on a timescale faster than in the Thommes et al. simulations. Mutual collisions would inhibit the transport of scattered particles to large semimajor axis. Therefore, given that more sophisticated models are no more likely to produce orbits like those of 2000 $CR_{105}$ and 2002 $VB_{12}$, we believe that an eccentric Neptune at early epochs cannot be a plausible explanation for the origin of the orbit of 2000 $CR_{105}$ or 2003 $VB_{12}$.

## 3. ROGUE PLANET

Morbidelli & Valsecchi (1997) and Petit et al. (1999) have proposed that an Earth-mass body, scattered outward by Neptune, might have caused the orbital excitation observed in the trans-Neptunian region. More recently, Brunini & Melita (2002) proposed that a planet on a moderate-eccentricity orbit with $a \sim 60$ AU could explain the putative edge of the Kuiper belt at $\sim$50 AU (Allen et al. 2002; Trujillo & Brown 2001). Although detailed investigations seem to indicate that these scenarios (often nicknamed the "rogue-planet scenarios") cannot be responsible for the observed Kuiper belt structure (see Morbidelli et al. 2003 for a discussion), it is worth briefly investigating whether a rogue planet in the Kuiper belt or in the scattered disk could explain the origin of 2000 $CR_{105}$ or 2003 $VB_{12}$.

We consider a scenario similar to that proposed by Petit et al. (1999), who speculated on the existence of massive bodies in the scattered disk during the early epochs of the solar system. To accomplish this, we followed the evolution of a system containing the four giant planets, a number of embryos initially between Uranus and Neptune, and 983 test particles for 1 Gyr. In order to put ourselves in the most favorable position to generate objects on orbits like those of 2000 $CR_{105}$ and 2003 $VB_{12}$, we considered the extreme and unrealistic case of initially having 10 half–Earth-mass embryos in the system. The test particles were initially placed between 25 and 35 AU or between 40 and 50 AU, on quasi-circular coplanar orbits.

During the simulation, all the embryos at some point found themselves in the scattered disk, with $a > 30$ AU. Of them, six temporarily reached a semimajor axis larger than 100 AU. Some of the embryos remained in the system for a long time, where they could presumably scatter the test particles. Indeed, five embryos had a lifetimes longer than 100 Myr, and two survived to the end of the integration. The surviving embryos were still Neptune-crossing, however, so they are presumably not stable.

Figure 2*a* shows the (*a*, *q*)-region covered by the test particles during the simulation. It was generated using the procedures described above for generating Figure 1. The region visited by our test particles marginally overlaps the orbit of 2000 $CR_{105}$. However, if this scenario were correct, we would expect many more objects with perihelion distances similar to 2000 $CR_{105}$ but with smaller semimajor axis, which has never been observed. This problem is not alleviated by considering only particles that survive for a long time in the simulation. Believing that the lack of low-*a*, large-*q* objects in the observed sample is significant, we tend to dismiss the Petit et al. (1999) model for the origin of the orbit of 2000 $CR_{105}$. Moreover, the orbit of 2003 $VB_{12}$ would require another mechanism, because it lies very far from the boundary of this distribution.

We have also considered an Earth-mass planet initially on an orbit similar to that postulated by Brunini & Melita (2002), with $a = 62.83$ AU, $e = 0.2$, and $i = 6°$. This planet has the advantage of having an aphelion distance at ~75 AU, which is very close to the perihelion distance of 2003 $VB_{12}$. It therefore seems to be a good candidate to emplace objects at the locations of both 2000 $CR_{105}$ (which would be a deep planet-crosser) and 2003 $VB_{12}$.

We have integrated for 4 Gyr the orbits of 100 test particles initially on circular and coplanar orbits between 60 and 90 AU under the gravitational influence of the Sun, the four giant planets, and the rogue planet. The result is shown in Figure 2*b*, with the same representation used in Figure 1. Unlike in the previous plots of this paper, only the last 2 Gyr of evolution are used to compute of the region covered by the particles. The orbit of 2000 $CR_{105}$ is reproduced! Moreover, for the particles with 40 AU $< q <$ 50 AU the semimajor-axis distribution peaks nicely at 200 AU. Thus, this mechanism is consistent with the fact that we have not found objects with the same $q$ as 2000 $CR_{105}$ but with smaller semimajor axes.

However, we caution that our test-particle density distribution near the position of 2000 $CR_{105}$ is due to a *single* particle, which is scattered into that region at $t = 720$ Myr and then evolves in a quasi-stable manner for the age of the solar system. Hence, our apparently nice result above suffers from small number statistics.

Moreover, the orbit of 2003 $VB_{12}$ remains well beyond the reach of the particles scattered by the rogue planet. Even on a timescale of 4 Gyr, an Earth-mass planet has difficulty transporting objects much farther than $a \sim 250$ AU. This simulation shows that the naive expectation that a planet would populate the entire orbital region that crosses its own orbit is not correct. An Earth-mass planet at the edge of the Kuiper belt simply cannot transport objects from a nearly circular orbit to large semimajor axes over the age of the solar system without first handing them off to Neptune.

Having said this, given the small number of experiments we have thus far performed, we of course cannot rule out that there is a combination of planet mass and distance that can produce both 2000 $CR_{105}$ and 2003 $VB_{12}$. There is a huge parameter space of possibilities that cannot be exhaustively covered in a practical way.

In addition, our results show that it would take a long time to create an orbit like that of 2003 $VB_{12}$. So, any trans-Neptunian planet that could make this orbit would, most likely, need to be in the solar system today. The presence of one or more planets in the distant solar system would raise severe questions, such as, How did these planets form so far from the Sun? How were these planets transported to their current distant location? Is their formation or transport compatible with the observed properties of the Kuiper belt and with the orbital distribution of the other giant planets? Why have these planets not yet been observed? Science should always give preference to the most simple theories—ones that do not raise more problems than they solve. We are convinced that the rogue-planet scenario does not fall into this category. A much more credible scenario for the origin of the orbits of 2000 $CR_{105}$ and 2003 $VB_{12}$ is presented in § 5; another possible one is in § 6.

## 4. PERTURBATIONS FROM A TRANSIENT, MASSIVE TRANS-NEPTUNIAN DISK

In this section, we present a wholly new idea for the formation of 2000 $CR_{105}$—another which, unfortunately, fails to work. We present this mechanism for completeness and because we believe that the dynamics presented here could be of use in the future.

Imagine that a massive and dynamically cold trans-Neptunian disk of planetesimals persisted for a long time. This disk would have exerted perturbations on bodies with large semimajor axes and moderate-to-large inclinations, similar to those exerted by the Galactic disk on Oort cloud comets. As a consequence, as scattered-disk bodies evolved outward they would have entered a phase during which their inclinations and perihelion distances would have been oscillating because of the presence of this disk. If this disk, or at least part of it, dispersed while some objects were in this phase, some of them would have been left with large perihelion distances.

The secular evolution induced on small bodies by the four giant planets (assumed to be on coplanar and circular orbits) and a massive disk situated on the planets' orbital plane can be analytically computed with a trivial adaptation of the approach usually followed to compute the effects of the Kozai resonance (see Thomas & Morbidelli 1996; Morbidelli 2002). The evolution of the eccentricity and of the argument of perihelion $\omega$ are coupled, while the semimajor axis and the quantity $H = [a(1-e^2)]^{1/2} \cos i$ remain constant. Figure 3 shows the possible trajectories on the $(\omega, q)$-plane for $a = 230$ AU and $H = 8.329$, which are the values corresponding to the current orbit of 2000 $CR_{105}$, once its inclination is computed with respect to the invariant plane of the four giant planets. The massive disk is assumed to extend from 40 to 120 AU in the case illustrated in Figure 3*a* and from 70 to 120 AU in the case illustrated in Figure 3*b*. Both disks had the same surface density, $\Sigma \propto r^{-2}$, which is a simple extrapolation of the surface density of solid material in the region of the giant planets (Weissman & Levison 1997). Thus, the total mass of the disk on the left was 94 $M_\oplus$, while the total mass of the disk on the right was 46 $M_\oplus$.

As one can see, as the inner edge of the disk moves outward from 40 to 70 AU the libration region increases in width. Consider now initial conditions with $q \sim 38$ AU at $\omega = 0$. If the inner edge of the disk is at 40 AU, these initial conditions give orbits that have only moderate oscillations in perihelion distance while $\omega$ precesses. If the inner edge of the disk is at 70 AU, they give orbits that are in the libration region and along which $q$ eventually increases beyond 44 AU. The timescale for this increase is on the order of a few million years. For bodies with higher inclination (smaller value of $H$) than 2000 $CR_{105}$, the change in perihelion distance is enhanced, while for bodies with smaller inclination it is less pronounced.

From these results, we can tentatively envision the following scenario: Neptune dispersed the bodies in its vicinity, forming a scattered disk (Levison & Duncan 1997; Dones et al. 2004); assuming that the planet was more or less on its current orbit, the perihelion distances of the scattered-disk bodies with large semimajor axes ranged up to ~38 AU. Because of the perturbations generated by the massive disk, the scattered-disk bodies with moderate or high inclinations suffered oscillations in perihelion distance, coupled with the precession of their perihelion argument $\omega$. A massive disk could have undergone significant collisional erosion.[2] If so, collisional processes would have worked more effectively at the inner edge of the disk (because of the shorter orbital periods and larger surface densities), thereby causing an inside-out erosion of the massive disk. The effect would be equivalent to moving the inner edge

[2] Although it is unclear whether collisional grinding could have really been substantial without violating several constraints on the architecture of the outer solar system (see Morbidelli et al. 2003 for a discussion).

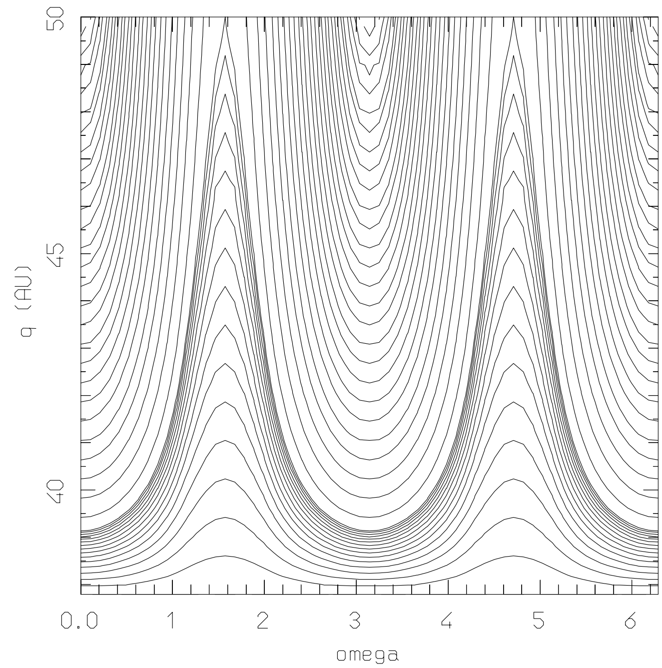


FIG. 3*a*

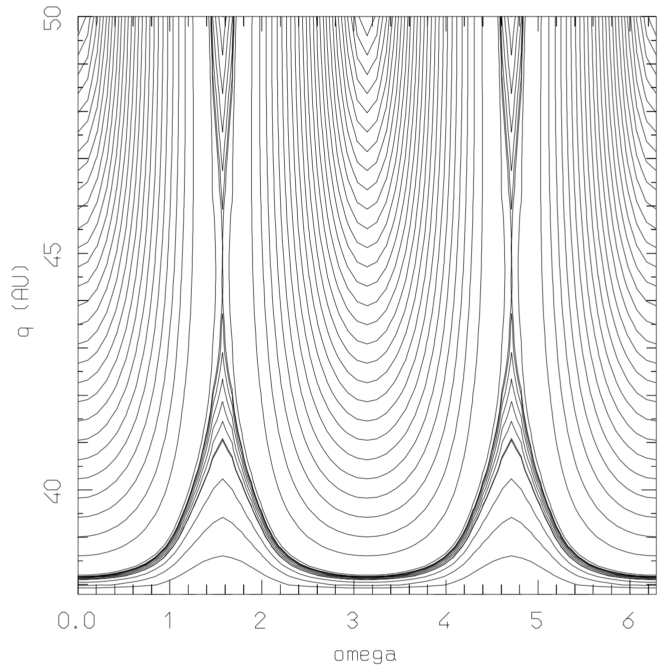


FIG. 3*b*

FIG. 3.—Secular ($\omega$, $q$)-evolution induced by the four giant planets and disks of (*a*) 94 $M_\oplus$ between 40 and 120 AU and (*b*) 46 $M_\oplus$ between 70 and 120 AU. Both panels are computed for small bodies with $a = 230$ AU and $H = [a(1-e^2)]^{1/2} \cos i = 8.329$ (the current value of 2000 $CR_{105}$).

of the disk outward. As a consequence (compare Fig. 3*b* with Fig. 3*a*), the amplitude of the perihelion distance oscillations would have increased, and bodies with $a \sim 230$ AU and $H \lesssim 8.329$ (2000 $CR_{105}$ values) would have eventually been captured in the region of phase space where $\omega$ librates. As a result, these objects would have gone through phases in which their perihelion distance could get up to 44 AU or more. If eventually the entire disk lost its mass, the perturbations would have vanished and thus the perihelion distances of the bodies would have remained essentially frozen for the rest of the solar system's lifetime.

We have attempted to simulate this scenario with a numerical integration. We followed the evolution of 300 scattered-disk objects under the gravitational influence of the Sun, four giant planets, and a 96 $M_\oplus$ disk spread between 40 and 150 AU. The disk is divided into two parts, the inner part encompassing the region between 40 and 60 AU and the outer part encompassing the region beyond 60 AU. The mass of the inner part linearly decays to zero in 70 Myr, while that of the outer part decays in 300 Myr. The initial conditions for the test particles are a subset of the initial conditions in Levison & Duncan (1997).

We followed the evolution of these particles with a version of the RMVS3 integrator modified so that the gravitational potentials of the two parts of the disk were added to the equations of motion of both the planets and the particles. The orbital distribution of the particles at the time when the disk is totally dispersed is shown in Figure 4. None of the particles have a perihelion distance larger than 38 AU. We believe this result is due to the fact that close encounters with Neptune are so frequent that the particles do not have enough time to respond to the slow, secular forcing exerted by the disk. As a test, we performed a new simulation in which we removed the giant planets and kept the mass of the disk constant. We indeed observed that the particles with inclinations larger than 30° and semimajor axes in the 200–260 AU region had their perihelion distances lifted above 45 AU, in good agreement with the analytic estimates. Therefore, we are forced to conclude that this scenario for the origin of a highly inclined extended scattered disk does not work.

## 5. EFFECTS OF STELLAR ENCOUNTERS ON THE TRANS-NEPTUNIAN DISKS

Observing that the dynamical excitation in the Kuiper belt apparently increases with semimajor axis, Ida et al. (2000) suggested that this structure might record the hyperbolic

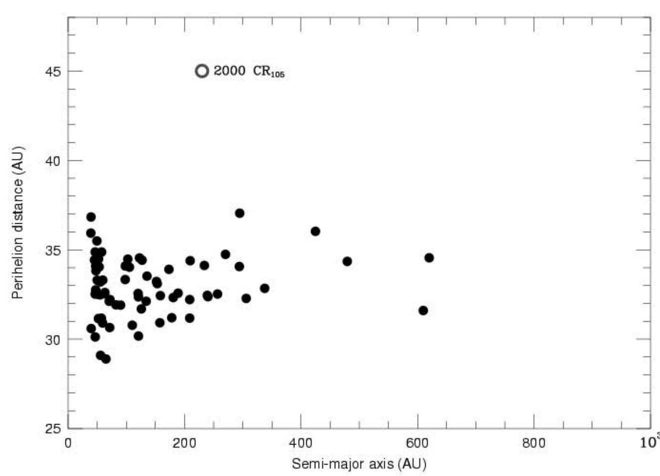


FIG. 4.—Distribution, after 300 Myr, of a set of scattered-disk particles (*filled circles*) that evolved under the gravitational influence of the four giant planets and a massive trans-Neptunian disk. The disk initially has 96 $M_\oplus$ between 40 and 150 AU; its inner part (41 $M_\oplus$ between 40 and 60 AU) is eroded in 70 Myr, while the remaining outer part is eroded in 300 Myr. No particles are found on orbits typical of the extended scattered disk. The open circle shows the location of 2000 $CR_{105}$.

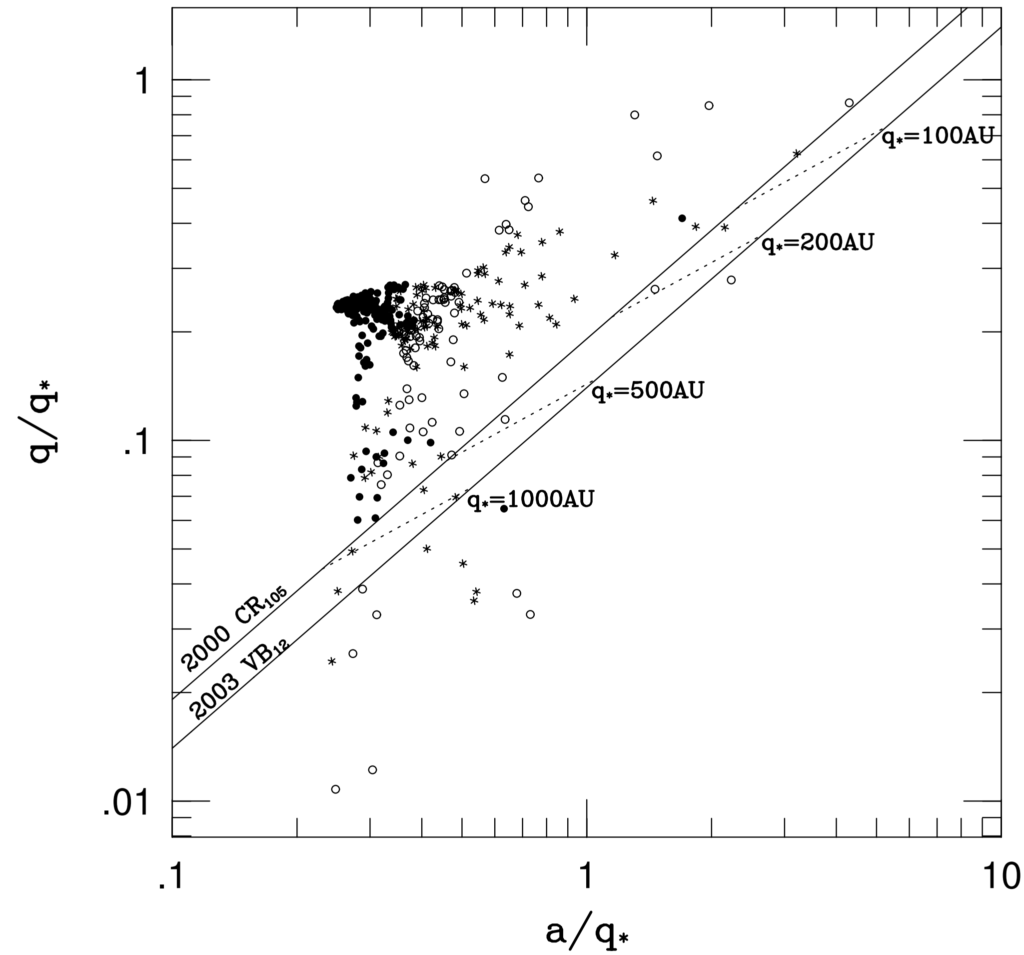


FIG. 5.—Distribution of perhelion distance ($q$) vs. semimajor axis ($a$) resulting from a solar-mass star passing an originally dynamically cold disk at a distance $q_*$. The passing star had $i_* = 20°$ and $\omega_* = 0$. The symbols represent its initial semimajor axis: the filled circles, asterisks, and open circles show particles with initial semimajor axes between $0.25q_*$ and $0.4q_*$, between $0.4q_*$ and $0.55q_*$, and between $0.55q_*$ and $0.71q_*$, respectively. The two solid lines show the orbits of 2000 $CR_{105}$ and 2003 $VB_{12}$ as a function of $q_*$. The dotted lines connect the orbits of the two objects at $q_*$ = 100, 200, 500, and 1000 AU.

passage of a solar-mass star at 100–200 AU from the Sun. With improved data, it now seems unlikely that the complexity of the orbital structure of the Kuiper belt can be explained by a stellar passage. However, the truncation of the Kuiper belt at ~50 AU might still be caused by such a passage (Kobayashi & Ida 2001; Melita et al. 2002; Levison et al. 2004). The details of such an encounter are described in a companion paper (Levison et al. 2004, hereafter LMD04).

In this section, we investigate whether a stellar encounter could be responsible for placing 2000 $CR_{105}$ and 2003 $VB_{12}$ onto their current orbits. In particular, we will examine two distinct scenarios: (1) These objects formed far from the Sun and were scattered from their primordial, nearly circular, trans-Neptunian orbits to their current orbits by a passing star. (2) These objects formed close to the Sun, were transported outward by the growing giant planets as scattered-disk members, and then were placed onto their current orbits by a passing star. We address scenario 1 first.

We performed a series of numerical experiments, using the RMVS3 orbit integrator (Levison & Duncan 1994),[3] of a passing star gravitationally interacting with a disk containing 500 massless test particles on nearly circular, coplanar orbits uniformly distributed about the Sun. The scale of the system is set by the perihelion distance of the star's hyperbolic orbit ($q_*$), and thus all distances are given in terms of this quantity. The disk particles were uniformly distributed about the Sun between $0.25q_*$ and $0.72q_*$. The eccentricities and inclinations (in radians) of the particles were set to 0.01, and the other angles were randomly chosen. We varied the star's encounter speed ($v_\infty$), its mass ($M_*$), its inclination ($i_*$), and its argument of perihelion ($\omega_*$). In total we studied 19 systems. These integrations are the same as those described in LMD04, to which the reader is referred for more details.

In roughly half the cases studied, we found that a close encounter between a star and dynamically cold disk can explain both 2000 $CR_{105}$ and 2003 $VB_{12}$. The most favorable case is shown in Figure 5, which plots the $q$-$a$ distribution of the disk particles after a passage of a 1 $M_\odot$ star with $v_\infty = 1$ km s$^{-1}$ (typical of star clusters), $i_* = 20°$, and $\omega_* = 0$, in terms of $q_*$. The symbols represent the ranges of initial semimajor axis (see figure legend). The two solid lines show the orbits of 2000 $CR_{105}$ and 2003 $VB_{12}$ for different values of $q_*$. The dotted lines connect the orbits of the two objects at four distinct values of $q_*$.

Figure 5 shows that this encounter can produce orbits for both the objects in question for various values of $q_*$. However, we are inclined to exclude many values of $q_*$ because of

[3] When we started this project, we were somewhat concerned that RMVS3 would not perform well in a system in which there was a perturber as massive as the Sun. So, we performed a series of tests comparing RMVS3 with a Bulirsch-Stoer integrator and found that RMVS3 performed flawlessly.

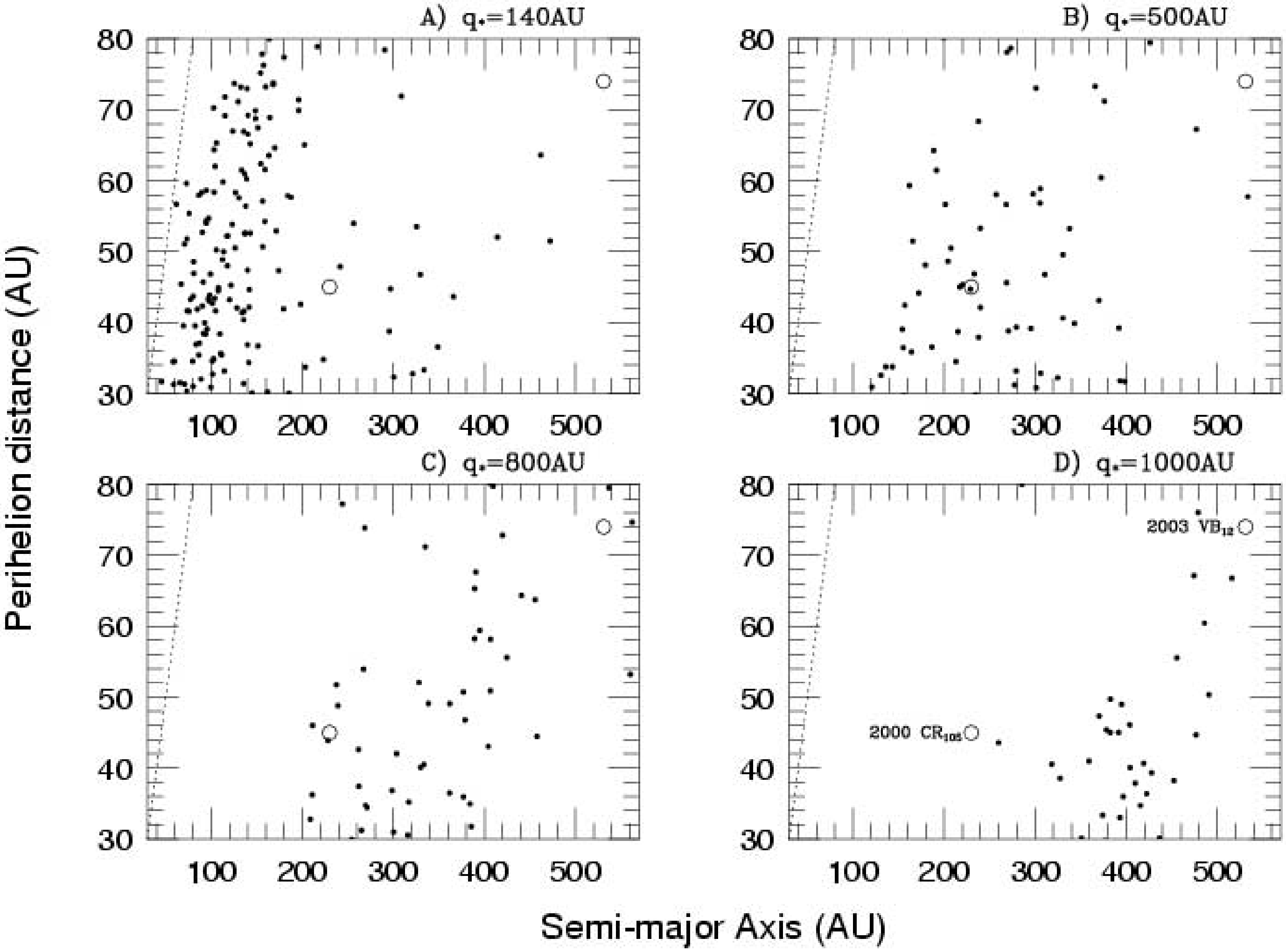


FIG. 6.—The extended scattered disk that resulted from a series of passing stars. In all cases the passing star was 1 $M_\odot$ and was on a hyperbolic orbit with $v_\infty = 0.2$ AU $yr^{-1}$, $\omega = 90°$, and $i = 45°$. The only thing that varies from panel to panel is the star's perihelion distance $q_*$. The particles were initially in the scattered disk that was created during Dones et al.'s (2004) simulations of Oort cloud formation. In particular, we took the scattered disk at $10^5$ yr into the Dones et al. simulation, but our results are not significantly affected by this choice. See LMD04 for more details. The two open circles show the orbits of 2000 $CR_{105}$ and 2003 $VB_{12}$.

the orbital element distributions they produce. Values of $q_* \lesssim$ 150 AU can be excluded because they excessively excite the Kuiper belt (LMD04). Values of $q_*$ between 150 and ~300 AU are unlikely because they produce a huge population of objects with perihelia between 30 and 60 AU and $a \sim 100$ AU, which has not been seen. Values of $q_*$ near 500 AU can also probably be excluded because they never created an orbit like that of 2003 $VB_{12}$ in any of our 19 simulations (i.e., we never created objects with $a/q_* \sim 1$ and $q/q_* \sim 0.15$).

However, as the figure shows, values of $q_*$ between ~500 and ~1000 AU do produce 2000 $CR_{105}$ and 2003 $VB_{12}$ analogs and not an overwhelming population of extended scattered disk objects with smaller semimajor axis. Note, though, that the objects that fall near the orbit of 2003 $VB_{12}$ are formed from the outer disk, that is, regions exterior to $0.4q_*$. So, we conclude that it is possible that in principle both 2000 $CR_{105}$ and 2003 $VB_{12}$ were scattered from distant, primordial, nearly circular orbits to their current orbits by a passing star. However, this requires that 2003 $VB_{12}$ have formed beyond ~200 AU. Our current understanding of the collisional growth of distant objects (Kenyon & Bromley 2004) seems to exclude this possibility, because 2003 $VB_{12}$ would take ~4 Gyr to grow to its current size on a circular orbit at this distance, and longer beyond. On the contrary, the stellar encounter most likely could not have occurred later than ~100 Myr, because of the damage it would do to the Oort cloud (as discussed below). Thus, unless the model timescales for the growth of objects are off by orders of magnitude, we believe that the scenario at issue here can most likely be ruled out.

We now turn our attention to the scattered disk as a source of 2000 $CR_{105}$ and 2003 $VB_{12}$. To accomplish this, we perform a series of simulations of stars passing through the solar system during the formation and dynamical evolution of the scattered disk and Oort cloud. We employ the simulations of Oort cloud formation by Dones et al. (2004, hereafter DLDW04).

We follow the procedures described in detail in LMD04, which we briefly review here: (1) We start with the simulation of the formation of the Oort cloud by DLDW04. From this simulation, we have a model of the time history of the Oort cloud and of the scattered disk. (2) We extract the position of planets and particles from the DLDW04 calculations at a specific time ($10^5$ yr, as a first attempt). (3) We integrate the orbits of these particles during a stellar encounter. Since this work is intended as a proof of concept, at first we restrict ourselves to a star on a hyperbolic orbit with $\omega = 90°$, $i = 45°$, and an unperturbed encounter velocity of 0.2 AU $yr^{-1}$, which is the

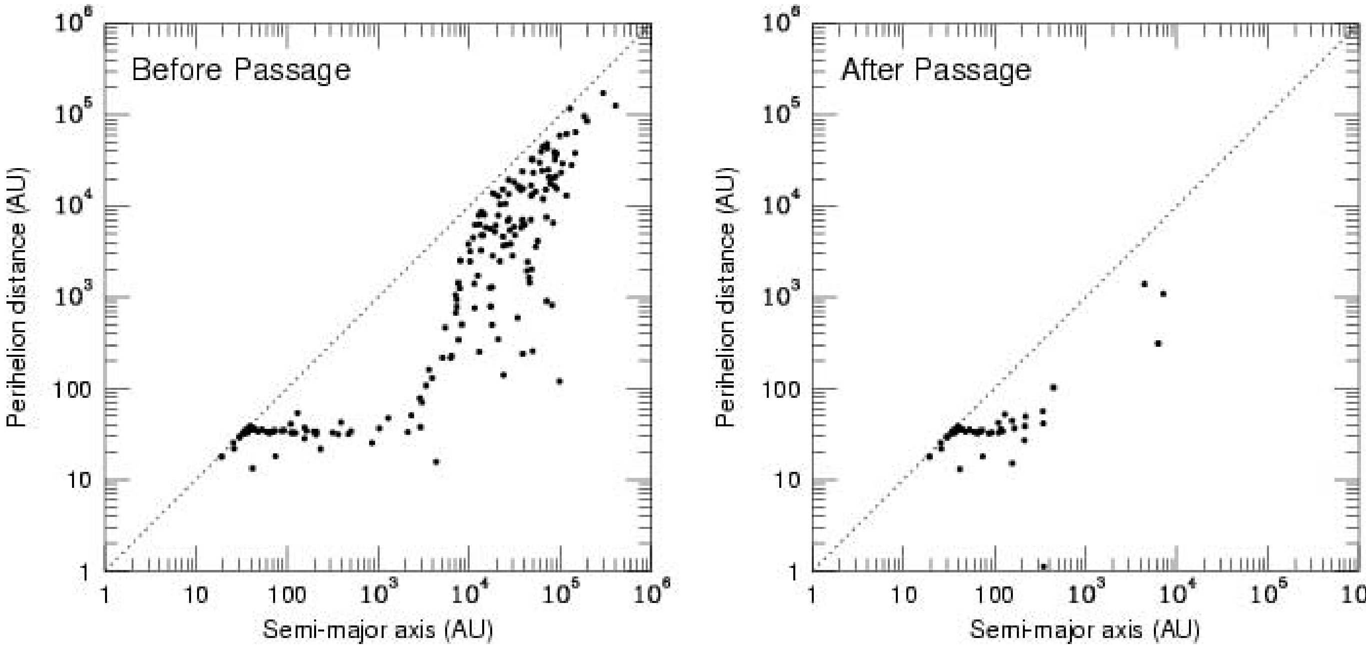


Fig. 7.—The *a-q* distribution of the Oort cloud before and after our nominal stellar passage with $q_* = 800$ AU at 1 Gyr. The left panel is taken directly from the simulations in Dones et al. (2004). The right panel shows the effect of such a passage. Note that the Oort cloud is decimated. We conclude that the stellar encounter that emplaced 2000 $CR_{105}$ and 2003 $VB_{12}$ on their current orbits occurred early in the history of the solar system.

typical relative velocity of stars in a star cluster (1 km $s^{-1}$; Binney & Tremaine 1987). This choice is justified because the deep encounters required for the origin of 2000 $CR_{105}$ and 2003 $VB_{12}$ are likely to occur only when the Sun was embedded in a star cluster. Thus, in this first series of runs the only characteristics of the encounter we vary are the perihelion distance of the star and its mass. In particular, we studied stars with $\frac{1}{10}$, $\frac{1}{4}$, and 1 $M_\odot$. However, since our results are not qualitatively affected by the mass of the star, we concentrate on the 1 $M_\odot$ case.

Figure 6 shows the results of our simulations for a 1 $M_\odot$ star with four different values of its perihelion distance ($q_*$): 140, 500, 800, and 1000 AU. In all cases but the $q_* = 1000$ AU run, objects like 2000 $CR_{105}$ and 2003 $VB_{12}$ are created. The $q_* = 1000$ AU run is simply too weak to produce these objects.

However, as we explained in § 1, we believe that one of the important characteristics that we need to explain with these models is the dearth of observed objects with perihelion distances comparable to 2000 $CR_{105}$ but with smaller semimajor axes. If this is indeed the case, then we can place some constraints on $q_*$. Small perihelion passages, like those required to sculpt the outer edge of the Kuiper belt (LMD04), are not ideal, because they tend to place too many objects on large-$q$ orbits close or interior to 100 AU. The run shown in Figure 6*a*, for example, has 17 objects with 42 AU $< q <$ 48 AU and $a <$ 150 AU, but only six in the same range of $q$ and with $a >$ 150 AU. Since observational biases tend to favor the discovery of objects with smaller semimajor axes, it is difficult to reconcile this model with the observations. Consequently, if the edge of the Kuiper belt was really formed by a stellar encounter at ~150 AU, the event that placed 2000 $CR_{105}$ and 2003 $VB_{12}$ onto their current orbits probably occurred afterward.

At larger $q_*$'s, the models begin to look like the distribution that we believe the data are indicating. In both the $q_* = 500$ AU run and the $q_* = 800$ AU run, there is a sharp transition interior to which there are no objects with large $q$. But exterior to this boundary, the star strongly perturbed the scattered disk and many objects were lifted to $q \sim 45$ AU or beyond. This sharp transition in semimajor axis between perturbed and nonperturbed bodies has already been observed by Kobayashi & Ida (2001). Similar results were found by Fernández & Brunini (2000). For the 1 $M_\odot$ stars studied here, this transition occurs at ~200 AU (roughly the semimajor axis of 2000 $CR_{105}$) when $q_* \sim 800$ AU. This "best-fit" value of $q_*$, however, is a function of the stellar mass and of the encounter circumstances. For the $\frac{1}{4} M_\odot$ simulations, the "best-fit" $q_*$ is ~400 AU, while for the $\frac{1}{10}$ $M_\odot$ case it is ~200 AU. We also performed some runs where we varied the inclination of the star and found that the inclination of the star's orbit does not seem to affect $q_*$ significantly.

LMD04 set some constraints on the time when the putative stellar encounter that truncated the Kuiper belt could have occurred, by looking at the ratio between the scattered-disk population and the extended scattered disk population in the 50 AU $< a <$ 100 AU region. Unfortunately, we cannot repeat the same exercise here, because this more distant encounter affected only the bodies with $a >$ 200 AU, and in this region the number of *known* objects in both the scattered disk and the extended scattered disk is still too limited for statistical considerations. However, a stellar encounter capable of lifting the perihelion distance of 2003 $VB_{12}$ would have stripped the Oort cloud population that existed at the time of the encounter. For illustrative purposes, in Figure 7 we show the scattered disk and the Oort cloud before and after the passage of a solar-mass star at 800 AU from the Sun at 1 Gyr. Note that the Oort cloud is stripped from the system and that there is almost no material left in the scattered disk to rebuild it. Indeed, using the methods developed in LMD04, we find that in this case the current Oort cloud would only contain 8% of the material that it would have if the encounter never happened. Similarly, we lean toward excluding all encounters happening later than a few hunder million years, because they would produce an Oort cloud that is too anemic. An analogous result holds for the case of a $\frac{1}{10} M_\odot$ star encountering the Sun at $q_* = 200$ AU, because it would strip away ~80% of the Oort cloud that existed at the encounter time.

The time of the encounter is also the key parameter that controls the mass of the population transferred from the scattered disk to the extended scattered disk by the stellar encounter. This is because the mass and the orbital distribution of the scattered disk are sensitive functions of time. For example, according to DLDW04's model, the encounter is unlikely to have occurred either much before $\sim 10^5$ yr or after $\sim 5 \times 10^8$ yr, because during these times there was not enough material in the scattered disk to produce a significant population of objects like 2003 $VB_{12}$ and 2000 $CR_{105}$.

Indeed, the efficiency of delivery may be a problem with this whole scenario. Brown et al. (2004) estimated that the mass of the objects on 2003 $VB_{12}$–like orbits ($M_{VB12}$) is 5 $M_\oplus$, with very large uncertainties. However, we can show that this scenario cannot capture this much material in an extended scattered disk. In particular, $M_{VB12}$ is the product of the amount of material in the scattered disk with 400 AU $\lesssim a \lesssim$ 600 AU at the time of the encounter [$M_{sd}(t)$] and the probability that an object with a semimajor axis in this range will have its perihelion lifted above 50 AU by the encounter ($f_c$). We choose the 400–600 AU range because the stellar encounter changes the perihelion distances of the bodies, leaving their semimajor axes almost unaffected. Therefore, the bodies that can be emplaced on orbits similar to that of 2003 $VB_{12}$ must come from this region. DLDW04's model predicts that $M_{sd}(t)$ is at most 0.5% (which occurred at $10^6$ yr) of the initial total disk mass initially between 4 and 40 AU, $M_{disk}$. In our nominal simulation (a solar-mass star with $q_* = 800$ AU), $f_c = 0.80$. So, $M_{VB12} \approx 0.004 M_{disk}$. Brown et al.'s estimate of $M_{VB12}$ implies that $M_{disk} > 1000\ M_\oplus$.

Such a huge mass is unlikely because, according to the simulations of Hahn & Malhotra (1999) and Gomes et al. (2004), such a massive planetesimal disk would have forced Neptune to migrate well beyond 30 AU. However, the estimate by Brown et al. is very uncertain, being based on the statistics of one object. The authors themselves recognize that if their estimate were true, many other smaller objects on 2003 $VB_{12}$–like orbits should have already been discovered by deeper Kuiper belt surveys. If the total mass in the region is only of a few tenths of an Earth mass (which is still statistically consistent with the discovery of one 2003 $VB_{12}$ in Brown et al.'s survey), then the total mass of the planetesimal disk comes down to about 50 $M_\oplus$, compatible with our current understanding of planetary migration. However, if Brown et al.'s estimate is correct, then we can probably rule out this scenario. A mechanism that, in principle, could have emplaced Earth masses of material on 2003 $VB_{12}$–like orbits will be discussed in § 6.

## 6. CAPTURE OF EXTRASOLAR PLANETESIMALS

This section is devoted to a new mechanism that, in principle, could have delivered several Earth masses of material into the 2003 $VB_{12}$ region—the Sun could have captured a substantial fraction of the planetesimal disk of a small star or of a brown dwarf that it encountered while it was still in its birth cluster. As discussed above, during the early evolution of the solar system the Sun was most likely in a young star cluster, where encounters between stars would have been common. Clarke & Pringle (1993) showed that deep, low-velocity encounters between two stars of the same mass can lead to a significant transfer of material between the stars but would also lead to the disruption of both star's protoplanetary disks. Thus, since low-mass stars and brown dwarfs are the most common stars in clusters (Chabrier 2003 and reference therein), in this section we ask whether an encounter between a low-mass star and the Sun could produce objects on orbits like 2000 $CR_{105}$ and 2003 $VB_{12}$ while leaving the Sun's protoplanetary disk unperturbed within, at least, 50 AU.

The answer to the above question is yes. Indeed, Figure 8 shows the temporal evolution of an encounter consisting of particles originally in a disk around a 0.05 $M_\odot$ star that passes 200 AU from the Sun. The orbital velocity of the star relative to the Sun was assumed to be 1 km $s^{-1}$, typical of a cluster, as discussed in the previous section. The interloping star's disk was assumed to extend from 20 to 100 AU and to lie in the same plane as the encounter. In this simulation, 44% of the extrasolar protoplanetary material evolved onto bound orbits around the Sun. Figure 9 shows the final *heliocentric* semimajor axes and perihelion distances of the bound particles. As the figure shows, the orbit of 2003 $VB_{12}$ is consistent with the resulting distribution for the captured extrasolar planetesimals, and that of 2000 $CR_{105}$ is also (barely) reproduced.

A detailed exploration of the capture process, which might also be relevant to different problems, such as the origin of the Oort cloud or the origin of the irregular satellites of the giant planets, will be the subject of a forthcoming paper. However, from a preliminary exploration of the parameter space, we find that the key parameters that govern the capture efficiency are the inclination of the disk relative to the stellar-encounter plane, the mass of the star, and its encounter distance. The capture efficiency is large if the inclination is small or moderate. For the above example, the capture efficiency is about 30%–40% for inclinations smaller than 30°; it decreases roughly linearly to 10%–20% as the inclination increases to 90° and then drops to zero in the next 40°. The mass of the star, the encounter distance, and the radial extent of the disk also govern the overall efficiency of the process, since only the planetesimals near or beyond the Hill sphere of the star at perihelion can be stripped from the parent object.

The final heliocentric orbital distribution of the captured planetesimals also depends on the mass of the star and its encounter distance. In particular, the semimajor axes of the resulting heliocentric orbits are mostly determined by the mass of the interloping star—the larger the mass, the smaller the semimajor axes. On the other hand, the perihelion distances of the bound objects are generally half that of the closest-approach distance of the star and are mainly independent of the star's mass. In all the cases we ran (although they are few in number), we find that for any given run, bound objects with larger semimajor axes tend to have smaller $q$'s. Thus, it may be difficult to find a single encounter that can easily produce the orbits of both 2000 $CR_{105}$ and 2003 $VB_{12}$. This is a weakness of this scenario. One possible solution to this difficulty is that 2000 $CR_{105}$ and 2003 $VB_{12}$ were placed on their orbits by a single encounter, but 2003 $VB_{12}$ was captured from the passing star while 2000 $CR_{105}$ had its $q$ lifted from a normal scattered-disk orbit, as described in the previous section.

Given that the dynamics of this process works, at least to zeroth order, the remaining issue is whether such an encounter is likely to have occurred. Recent observations have shown that brown dwarfs are roughly as common as stars in young clusters (Chabrier 2003 and reference therein), and thus the encounters described in this section are about as likely as those described in the previous one (i.e., those required to lift the perihelion of

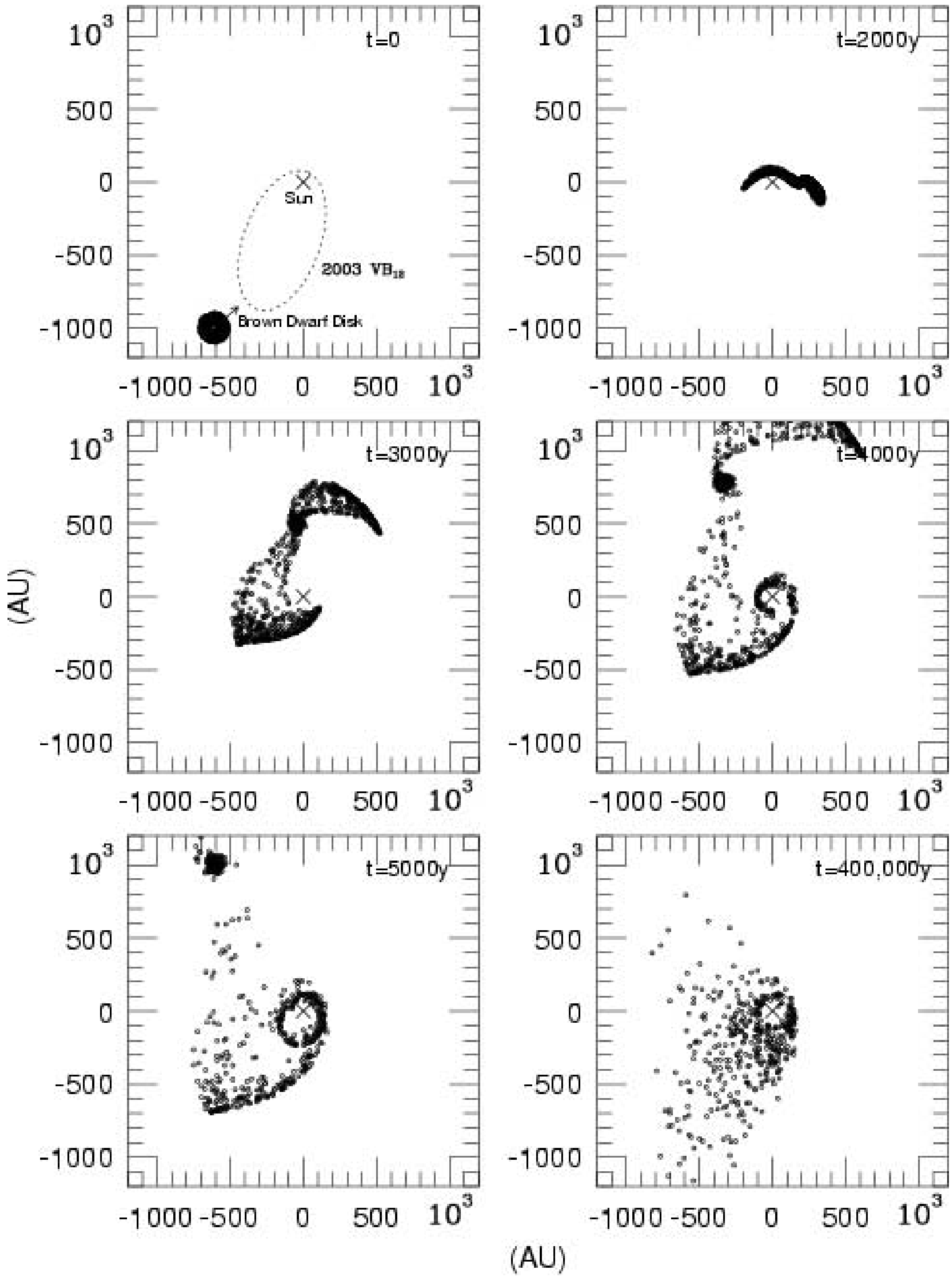


FIG. 8.—Temporal evolution of a stellar encounter that leads to the capture of extrasolar material. Each panel shows the positions of massless test particles (*open circles*), the Sun (*large cross*), and a passing brown dwarf (*large filled circle*) in the plane of the encounter, at six different times. See text for a description of the encounter. The time given in the upper right of each panel is with respect to an arbitrary zero point.

objects in heliocentric orbits). In addition, approximately 65% of young brown dwarfs have an infrared excess, which suggests the presence of an accretional disk (Muench et al. 2001). The main uncertainly is that we do not know anything about these disks. In particular, we do not know the size of their constituent particles (i.e., whether objects as large as 2000 $CR_{105}$ and 2003 $VB_{12}$ exist) or their radial extent. However, given that even the giant planets formed large objects in their own accretional disks (e.g., the satellite systems around Jupiter and Saturn), we think that it is plausible that planetesimal disks typically exist around low-mass stars, possibly accounting for several Earth masses of material.

## 7. CONCLUSIONS AND DISCUSSION

We have analyzed with numerical simulations five seemingly promising mechanisms for explaining the origin of the peculiar extended scattered disk objects 2000 $CR_{105}$ and 2003 $VB_{12}$: (1) a high-eccentricity phase of Neptune, (2) the existence of a rogue planet in the Kuiper belt or the scattered disk, (3) the effect of a transient, massive, and dynamically

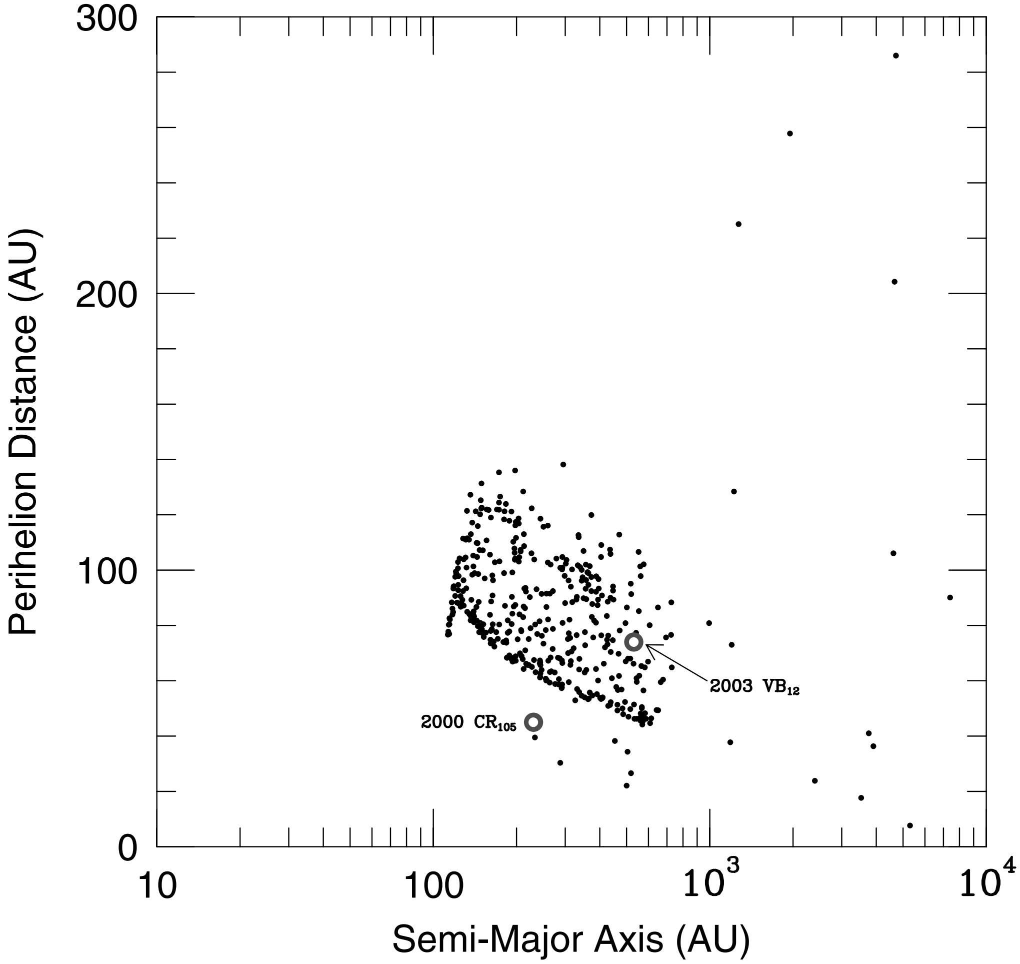


FIG. 9.—The $a$-$q$ distribution of the objects captured during the encounter shown in Fig. 8. The simulated objects are indicated by the filled circles, while the locations of 2000 $CR_{105}$ and 2003 $VB_{12}$ are indicated by open circles.

cold trans-Neptunian disk, (4) the excitation of the trans-Neptunian population by a passing star, and (5) the capture of extrasolar planetesimals from a low-mass star encountering the Sun. We remind the reader that an alternative scenario, in which a small fraction of the objects of an early, massive scattered disk population permanently acquired a large perihelion distance during the outer migration of Neptune, has recently been proposed by Gomes (2003a, 2003b).

Our simulations are all done in the framework of massless, noninteracting particles, undergoing the effects of massive perturbers (planets, stars, disk, etc.). This is of course a simplification. However, we believe that the dynamical processes that we neglect, such as mutual collisions and collective gravitational effects, would not significantly change the results of our simulations. Indeed, these effects typically play an important role in the response of dynamically cold disks to distant, gentle perturbations. All the scenarios that we explore here, conversely, involve violent, impulsive phenomena such as gravitational scattering. So, we believe that our simplifications are valid.

Of the six mechanisms outlined above, only the two related to early stellar passages appear satisfactory. By satisfactory, we mean capable of producing the orbits of both 2000 $CR_{105}$ and 2003 $VB_{12}$ at the same time, without generating a larger population of extended scattered disk objects with smaller semimajor axis. All the other mechanisms, including that of Gomes, do not seem capable of reproducing the orbit of 2003 $VB_{12}$, and when they seem effective for 2000 $CR_{105}$, they typically predict the existence of a much larger population with $q \sim 45$ AU but $a < 200$ AU. In our analysis, we put a great deal of emphasis on the absence of detections of bodies with such orbital characteristics. Since observational biases (given an object's perihelion distance and absolute magnitude, and a survey's limiting magnitude of detection) sharply favor the discovery of objects with small semimajor axes, we believe that it would be unlikely that the first two discovered bodies with $q > 44$ AU had $a > 200$ AU if the real semimajor-axis distribution in the extended scattered disk were skewed toward smaller $a$. Therefore, we prefer the scenarios that produce large-$q$ bodies only at large semimajor axis.

Of the mechanisms studied here, only the stellar-encounter scenarios match this restriction, although not all of them do. In particular, we are inclined to dismiss the idea that 2000 $CR_{105}$ and 2003 $VB_{12}$ were extracted from a distant Kuiper belt during a close stellar encounter that produced the currently observed outer edge of the belt at $\sim$50 AU, for the same reason.

Among the stellar-encounter scenarios left, we are inclined to favor that of a star lifting the perihelion distances of scattered-disk objects with large semimajor axes. We think that, in addition to better fulfilling the current observational constraints, this scenario has aesthetic advantages. In contrast to the capture scenario, which is fraught with unknowns, it has many fewer uncertainties. The existence of the active scattered disk and the Oort cloud strongly argues for a massive scattered disk early in the solar system's history. In addition, it is now quite accepted that the solar system formed in cluster associations, where close encounters are frequent (Bate et al. 2003). Indeed, since its discovery, passing stars have been used to perturb objects into the Oort cloud (Oort 1950). In particular, in recent years several authors have simulated the formation of a massive Oort cloud in a dense stellar environment (Eggers et al. 1997, 1998; Fernández & Brunini 2000), obtaining inner Oort cloud objects on orbits similar to that of 2003 $VB_{12}$. As a result, the "lifting" scenario easily fits into the current framework for the origin of the Sun, planets, and Oort cloud.

In this work we have shown that the total mass of the population in the 2003 $VB_{12}$ region produced by a passing star through the scattered disk can be as large as a few tenths of an Earth mass. If the real mass in this region turns out to be of several Earth masses, as suggested by Brown et al. (2004), then our attention should be turned to the second stellar-encounter scenario, in which the Sun captures a large fraction of the planetesimal disk of a low-mass star. This exotic scenario can, in principle, deliver a much larger amount of mass.

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