Stellar encounters as the origin of distant solar system objects in highly eccentric orbits

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The Kuiper Belt extends from the orbit of Neptune at 30 AU to an abrupt outer edge at ∼ 50 AU from the Sun. Beyond the edge is a sparse population of objects with large orbital eccentricities. Neptune shapes the dynamics of these objects, but the recently discovered planet 2003 VB12 (Sedna) has an eccentric orbit with a perihelion distance, 70 AU, far beyond Neptune’s gravitational influence. Although influences from passing stars could have created the Kuiper Belt’s outer edge and could have scattered objects into large, eccentric orbits, no model currently explains the properties of Sedna. Here we show that a passing star probably scattered Sedna from the Kuiper Belt into its observed orbit. The likelihood that a planet at 60–80 AU can be scattered into Sedna’s orbit is ∼ 50%; this estimate depends critically on the geometry of the flyby. Even more interesting, though, is the ∼ 10% chance that Sedna was captured from the outer disk of the passing star. Most captures have very high inclination orbits; detection of these objects would confirm the presence of extrasolar planets in our own Solar System.

In the planetesimal theory, planets grow from mergers of smaller, slowly-moving objects embedded in a gaseous, circumstellar disk surrounding a young star. For reasonable initial disk masses, this process yields 1000 km planets with roughly circular orbits in 50–100 Myr at 70 AU. To scatter a 1000 km planet into a Sedna-like orbit, a much larger planet must form at roughly the same distance. These more massive planets take at least 1 Gyr to form and should be rare. Despite extensive searches, none have been detected. Thus, in situ formation of a planet with Sedna’s current properties seems unlikely.

A chance encounter between the Sun and another star is a more plausible explanation for the orbit of Sedna. Previous numerical simulations show that a flyby of a solar-type star, with a distance of closest approach \( q_f \sim 150–200 \) AU, scatters objects at 60–80 AU into very eccentric orbits and truncates the Kuiper Belt at its observed edge. A more distant flyby, with \( q_f \sim 500–1000 \) AU, lifts objects from Neptune crossing-orbits into Sedna-like orbits, leaving the rest of the Kuiper Belt relatively unchanged. Although other mechanisms to truncate the Kuiper Belt are possible, they are inconsistent with the apparent formation of 1000 km planets in the larger disks observed around several nearby stars. Here we improve on previous flyby calculations and derive an initial orbital distribution of Kuiper belt objects from a detailed planet formation calculation. We then use a complete set of N-body simulations to provide the first estimates of the likelihood that a close encounter yields the observed edge to the Kuiper Belt and planets in Sedna-like orbits.
The discovery of Sedna also prompted us to consider an exciting new possibility, captures from the Kuiper Belt of the passing star\textsuperscript{16}. Like most stars, the Sun probably formed in a star cluster and experienced a close encounter with another cluster member\textsuperscript{24}. Encounters with field stars are unlikely\textsuperscript{25}. Cluster lifetimes of 100 Myr to 1 Gyr\textsuperscript{24} allow a solar-type star to produce 1,000 km objects as far out as 100 AU. Thus, both the Sun and the passing star probably had extended planetary disks at the start of their encounter. By analogy with galaxy collisions\textsuperscript{26,27}, the two stars can exchange a significant amount of outlying material during a flyby, depending on the geometry of the encounter and the properties of the planetary systems. Here we adopt a cluster age of 30–200 Myr for the encounter, and use planet formation and N-body simulations to provide the first assessment of the probability that a close pass yields the observed edge to the Kuiper Belt and the capture of an extrasolar planet into a Sedna-like orbit.

Consistent with formation in a star cluster with a velocity dispersion\textsuperscript{28} of 1 km s\textsuperscript{−1}, we assume the star and the Sun have equal mass and orbit as a marginally bound pair. Modest differences in starting conditions have no qualitative impact on our results. During the flyby, tidal shear dramatically increases orbital eccentricities in the disk at large heliocentric distances; objects closer to the Sun are unperturbed. Simulations that produce a sharp edge in the Kuiper Belt yield a correlation between $q_f$ and $i_f$, the inclination of the flyby trajectory relative to the invariable plane of the Solar System. For low-inclination orbits, where the passing star corotates with the disk, $q_f$ must exceed 120 AU to avoid disrupting the Kuiper Belt. Counterrotating flybys with $i_f = 90^\circ$–180$^\circ$ require smaller $q_f$ to produce the observed edge. The simulations suggest $i_f$(in degrees) $\sim 275 - 1.6q_f$. For a specific $q_f = 90$–160 AU, this expression yields $i_f$ to $\sim 10\%$ for corotating encounters and to $\sim 30\%$ for counterrotating orbits, where tidal shear is more broadly distributed in the disk and the edge is less sharp. In both cases, post-flyby collisional grinding removes additional material from the Kuiper Belt and accentuates the outer edge. Detailed collision models\textsuperscript{22,23} suggest that grinding and shear reduce the mass by 98\% to 99.9\%, close to observational estimates\textsuperscript{29}.

We may further constrain the passing star’s trajectory by assuming that Sedna is indigenous to the Solar System. Simulations then identify the flyby configurations that scatter objects into Sedna-like orbits, defined to have modest inclination ($i < 30^\circ$), and large eccentricity and perihelion distance ($e > 0.5$ and $q > 50$ AU). Fig. 2 shows results for two encounters where planets are scattered from nearly circular orbits at 80 AU into Sedna-like orbits, a corotating flyby with $q_f = 160$ AU and $i_f = 23^\circ$, and a counterrotating flyby with $q_f = 90$ AU and $i_f = 172^\circ$. Both flybys scatter $\sim 10\%$ of the objects from an annulus at 80±2.5 AU into high eccentricity orbits. After 50–200 Myr, our coagulation calculations produce 5–25 planets with radii of 500–2000 km at 80±2.5 AU. Thus, a flyby that makes the current edge to the Kuiper Belt also produces at least one indigenous object in a Sedna-like orbit. Roughly 95\% of these ‘successful’ flybys are corotating encounters. The chance of a Sedna-like orbit is fairly independent of the starting distance or the initial orbital eccentricity. Roughly 2\% of the 40–200 large planets formed in circular orbits at 60–80 AU scatter into a Sedna-like orbit. We derive similar results for the 50–500 planets with $e > 0.5$ and $q > 35$ AU in a ‘scattered disk’ (Fig. 3), suggesting that formation of a Sedna-like orbit from a scattered disk is 2–3 times more likely than formation from planets in initially cir-
cular orbits. Assuming both paths produce Sedna-like orbits, we predict 3–30 Sedna-like objects compared to the 30–100 estimated from the detection of a single Sedna at 90 AU.

Surprisingly, the probability that captured planets have Sedna-like orbits is also significant. When the trajectory of the Sun and the disk of the passing star corotate, the Sun captures up to a third of the extrasolar objects initially in orbit at distances of 60–80 AU from the passing star (Fig. 2). This ‘capture efficiency’ depends on \( q_f \) and the angle \( i'_f \) between the rotational axes of the two disks. The capture efficiency is 10% to 30% for \( q_f \leq 120 \text{ AU} \) and \( i'_f \leq 80^\circ \), and falls to \( \sim 5\% \) for \( q_f \sim 160 \text{ AU} \) and \( i'_f \leq 45^\circ \). For flybys with many captures, counterrotating flybys yield more Sedna-like objects than corotating flybys. For a random ensemble of flybys that produce the observed edge of the Kuiper Belt, the probability of a capture into a Sedna-like orbit is \( \sim 5\% \).

The probability estimates for indigenous and captured planets with Sedna-like orbits assume a flyby that produces the observed outer edge of the Kuiper Belt. Simple estimates of the evolution of star clusters indicate a reasonable probability, \( \sim 15\% \), for a stellar encounter within 160 AU during the first 1 Gyr of the solar lifetime\(^{24} \). Because the Sun is heavy enough to remain in the cluster as the cluster evaporates, 30% to 50% of the encounters probably occur during the first 100 Myr of the solar lifetime. Thus the total probability to produce at least one object with a Sedna-like orbit in the Solar System is reasonably large, \( \sim 5\% \) to 10% for an indigenous object and \( \sim 1\% \) for a captured object. These probabilities are significant compared to the chance of finding a Solar System like our own around any solar-type star, \( \sim 1\% \) or less\(^{24} \).

The simulations demonstrate that flybys leave unique signatures on the dynamics of the outer solar system. Corotating flybys produce a single population with orbital inclination \( i \sim 10^\circ \) at 100–500 AU; counterrotating flybys produce a cold population with \( i \leq 10^\circ \) and a hotter population with \( i \geq 30^\circ \) (Fig. 2). Flybys with an initial scattered disk of objects at 60–80 AU yield broader, but still distinct, distributions in inclination (Fig. 3). The two inclination populations of counterrotating flybys qualitatively resemble the two observed populations of Kuiper belt objects at 40–50 AU\(^{30} \). Systematic searches for high inclination objects in the outer Solar System can distinguish between corotating and counterrotating flybys and can estimate the relative fraction of objects in a scattered disk at the time of the flyby.

Orbits of individual objects also test the models. Some flybys produce objects with orbital elements similar to 2000 CR\(_{105}\), a \( \sim 1,000 \text{ km} \) planet with \( q = 44 \text{ AU}, e = 0.8, \) and \( i = 22^\circ \). Although 2000 CR\(_{105}\) is closer to Neptune than Sedna, the known planets probably cannot scatter 2000 CR\(_{105}\) into its present orbit\(^{7,16} \). The corotating flyby in Fig. 2 cannot produce orbits with the large range of inclination observed in Sedna and 2000 CR\(_{105}\), but counterrotating flybys yield a broad range encompassing the observations. Both types of flyby generate orbits similar to 2000 CR\(_{105}\) and Sedna from a scattered disk (Fig. 3; ref. 16). Long term simulations suggest that interactions with Neptune broaden the inclination distributions of corotating flybys, forming objects with orbital elements closer to both 2000 CR\(_{105}\) and Sedna. From these simulations, we
estimate that 2000 CR105 is 2–3 times more likely to be a captured planet than Sedna. Because our calculations are the only known way to produce high inclination objects, searches at high ecliptic latitude provide the best test of this picture for Sedna formation. Detection of objects with $i \geq 40^\circ$ would clinch the case for the presence of extrasolar planets in the outer Solar System.

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Figure 1 Stirring of the eccentricities of planets by the close pass of a Sun-like star. The star is on a marginally bound orbit corotating with the Sun's disk, with an orbital inclination of $i = 23^\circ$ and argument of perihelion $\omega = 212^\circ$. Each panel lists the distance of closest approach. The histograms show the frequency of the final eccentricity, $e_f$, for 20,000 particles initially in circular orbits at 40–80 AU around the Sun. Magenta histograms: fraction of orbits with $e_f < 0.04$; cyan histograms: fraction of orbits with $e_f < 0.2$; blue histograms: fraction of orbits with Sedna-like orbits ($e_f > 0.5$). The 160 AU encounter places the edge of the Kuiper Belt where observed, as indicated by the arrow in the middle panel.
Figure 2 Orbital elements of planets, formed in situ in the planetary disk, after the flyby of a 1 solar mass star as a function of final heliocentric distance. The planets have an initial probability $p$ of formation at in 1 AU bins at 40–80 AU derived from detailed planet formation calculations, $p \propto a^{-1}$, where $a$ is the semimajor axis. Left panels: a marginally bound, corotating flyby ($d_{\text{close}} = 160$ AU, $i = 23^\circ$, and $\omega = 212^\circ$). Right panels: a marginally bound counterrotating flyby ($d_{\text{close}} = 90$ AU, $i = 172^\circ$ degrees, and $omega = 130^\circ$). Large black circles: orbital elements of Sedna. Large black triangles: orbital elements of 2000 CR$_{105}$. In the upper panels, objects below the dashed lines cross the orbit of Neptune; in the middle panels, objects above the dashed lines cross the orbit of Neptune. Cyan points: planetary orbits initially distributed between 30–80 AU (Fig. 2), with initial eccentricity $e_0 = 0.02$ and initial inclination $i_0 = 0.5^\circ$. Blue points: orbits initially at $80 \pm 2.5$ AU with $e_0 = 0.05$ and $i_0 = 1^\circ$. Magenta points: objects captured by the Sun from the disk of the passing star. Each simulation consisted of 1,000 particles.
Figure 3 Orbital elements of planets, initially in a ‘scattered disk,’ after a flyby, as described in Fig. 2. The planets are placed initially at 40–80 AU with $p \propto a^{-1}$ as in Fig. 2, $q = 35$ AU, and $i_0 \leq 5^\circ$. Cyan points: planetary orbits initially distributed between 60–80 AU with perihelion distance of 35 AU. Blue points: orbits initially at $80 \pm 2.5$ AU, also with perihelion distance of 35 AU. The objects in the figure end up with a broader range of orbital elements than those in Fig. 2. While a subset of particles are consistent with both the orbits of Sedna and 2000 CR$_{105}$, the distributions are broader, reducing the correlations between the orbital elements of scattered objects and the good agreement between the observations and the models compared with the case of in situ formation shown in Fig. 2.