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DISCOVERY OF A CANDIDATE INNER OORT CLOUD PLANETOID

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ABSTRACT

We report the discovery of the minor planet (90377) Sedna, the most distant object ever seen in the solar system. Prediscovery images from 2001, 2002, and 2003 have allowed us to refine the orbit sufficiently to conclude that Sedna is on a highly eccentric orbit that permanently resides well beyond the Kuiper Belt with a semimajor axis of 480 ± 40 AU and a perihelion of 76 ± 4 AU. Such an orbit is unexpected in our current understanding of the solar system but could be the result of scattering by a yet-to-be-discovered planet, perturbation by an anomalously close stellar encounter, or formation of the solar system within a cluster of stars. In all of these cases a significant additional population is likely present, and in the two most likely cases Sedna is best considered a member of the inner Oort Cloud, which then extends to much smaller semimajor axes than previously expected. Continued discovery and orbital characterization of objects in this inner Oort Cloud will verify the genesis of this unexpected population.

Subject heading: Kuiper Belt — Oort Cloud — planetary systems: formation — solar system: formation

1. INTRODUCTION

The planetary region of the solar system, defined as the region that includes nearly circular low-inclination orbits, appears to end at a distance of about 50 AU from the Sun at the edge of the classical Kuiper Belt (Allen et al. 2002; Trujillo & Brown 2001). Many high-eccentricity bodies from the planetary region—comets and scattered Kuiper Belt objects—cross this boundary, but all have perihelia well within the planetary region. Far beyond this edge lies the realm of comets, which are hypothesized to be stored at distances of $\sim 10^4$ AU in the Oort Cloud. While many objects presumably reside in this Oort Cloud indefinitely, perturbation by passing stars or Galactic tides occasionally modifies the orbit of a small number of these Oort Cloud objects, causing them to reenter the inner solar system, where they are detected as dynamically new comets (Oort 1950; Duncan et al. 1987), allowing a dynamical glimpse into the distant region from which they came. Every known and expected object in the solar system has either a perihelion in the planetary region, an aphelion in the Oort Cloud region, or both.

Since 2001 November we have been systematically surveying the sky in search of distant slowly moving objects using the Samuel Oschin 48 inch (1.2 m) Schmidt Telescope at Palomar Observatory (Trujillo & Brown 2003) and the Palomar QUEST large-area CCD camera (Rabinowitz et al. 2003). This survey is designed to cover the majority of the sky visible from Palomar over the course of approximately 5 years, and when finished it will be the largest survey for distant moving objects since that of Tombaugh (1961). The major goal of the survey is to discover rare large objects in the Kuiper Belt that are missed in the smaller but deeper surveys that find the majority of the fainter Kuiper Belt objects (i.e., Millis et al. 2002).

In the course of this survey we detected an object with an R magnitude of 20.7 on 2003 November 14 that moved $4''.6$ over the course of three images separated by a total of 3.1 hr (Fig. 1). Over such short time periods, the motion of an object near opposition in the outer solar system is dominated by the parallax caused by the Earth's motion, so we can estimate that $R \approx 150/\Delta$, where R is the heliocentric distance of the object in AU and Δ is the speed in arcseconds per hour. From this estimate we can immediately conclude that the detected object is at a distance of ~ 100 AU, significantly beyond the 50 AU planetary region and more distant than any object yet seen in the solar system. The object has received the permanent designation (90377) Sedna.

Follow-up observations from the Tenagra IV telescope, the Keck Observatory, and the 1.3 m SMARTS telescope at Cerro Tololo between 2003 November 20 and December 31[1] allow us to compute a preliminary orbit for the object using both the method of Bernstein & Khushalani (2000, hereafter BK2000), which is optimized for distant objects in the solar system, and a full least-squares method that makes no a priori assumptions about the orbit.[2] Both methods suggest a distant eccentric orbit with the object currently near perihelion, but the derived values for the semimajor axis and eccentricity are very different, showing the limitations of fitting an orbit for a slowly moving object with such a small orbital arc. For such objects a time baseline of several years is generally required before an accurate orbit can be determined.

2. PREDISCOVERY IMAGES

For sufficiently bright objects, such the one discovered here, observations can frequently be found in archival data to extend

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[1] See http://cfa-www.harvard.edu/mpec/K04/K04E45.html for a table of astrometric positions.

[2] See http://www.projectpluto.com/find_orb.htm.

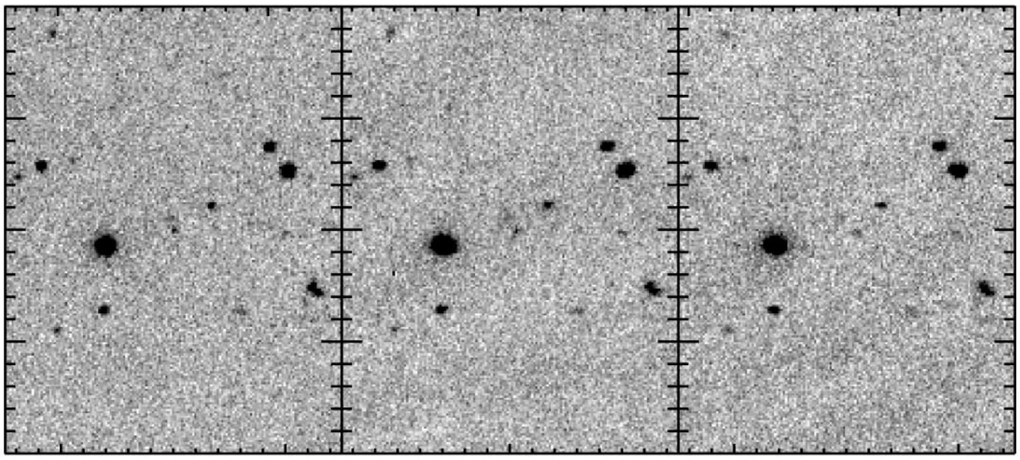

FIG. 1.—Discovery images of Sedna from the Palomar Samuel Oschin Telescope and the Palomar QUEST camera. The pixel scale is 0.″9 pixel^{-1} with north up and east left. The 150 s exposures were obtained 2003 November 14 at 6:32, 8:03, and 9:38 (UT), respectively. The object moves 4.″6 over 3.1 hr.

the time baseline backward in time. At each time that a new position in the past is found a new orbit is computed and earlier observations can then be sought.

The object should have been observed on 2003 August 30 and September 29 during drift scans from the Palomar QUEST Synoptic Sky Survey (Mahabal et al. 2003), also operating on the Samuel Oschin Telescope at Palomar Observatory. From the November and December data we predict positions for September 29 with an error ellipse of only 1.″2 × 0.″8 (although the two orbital determination methods disagree on precise orbital parameters, they both predict the same position within an arcsecond). A single object of the correct magnitude appears on the Palomar QUEST images within the error ellipse (Fig. 2). A search of other available archival sources of images of this precise region of the sky, including our own survey data, additional Palomar QUEST data taken on different nights, the Palomar Digitized Sky Survey images, and the NEAT Sky-Morph database,[3] finds no object that has ever appeared at this position at any other time. Below we refer to such detections that are seen on only one date as "unique detections." Unfortunately, individual images in the Palomar QUEST survey

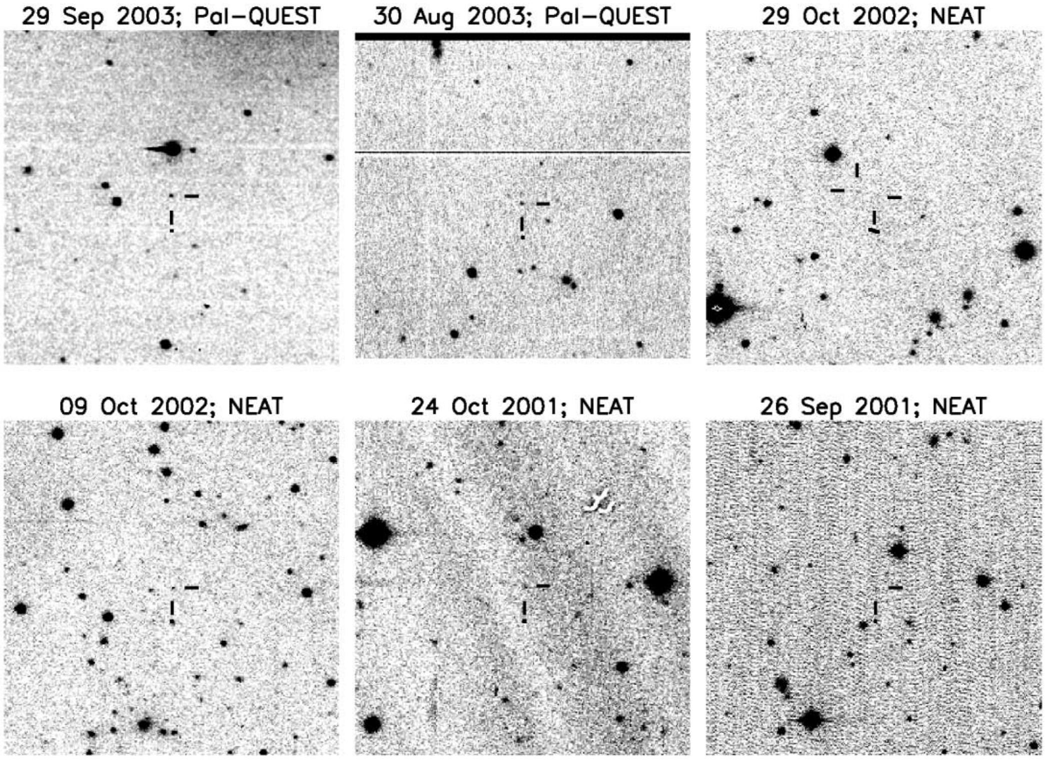

FIG. 2.—Prediscovery images of Sedna. Each image shows a 5′ × 5′ field centered on the predicted position of Sedna. The crosshairs mark the expected position, while the very small ellipse below the crosshairs shows the size of the error ellipse. In all cases the object is well within the error ellipse, and no similar object appears at the same position in any other data searched.

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[3] See http://skyview.gsfc.nasa.gov/skymorph.

are not taken long enough apart for us to determine if this object is moving or is instead a fixed source that was coincidentally bright only during the time of observation (a variable star, a supernova, etc.). We estimate the probability of an accidental unique detection within the error ellipse by examining the $5' \times 5'$ region surrounding this object to see if additional unique detections randomly occur. We find no such unique detections in the surrounding region; thus the probability of such a unique detection randomly occurring within the error ellipse appears less than 10^{-4}. We conclude that this detection is indeed a prediscovery image of Sedna.

Including this position in our orbit calculation shrinks the error ellipse for 2003 August 30—another night of Palomar QUEST observations—to less than an arcsecond. Examination of the 2003 August 30 Palomar QUEST image and other archival images of the same location shows a unique detection at precisely the predicted location. Again, no other unique detection is found within a $5' \times 5'$ surrounding box. We again conclude that this is our object with very low probability of coincidence.

From a 4 month baseline the orbital elements are still uncertain, but positions for the 2002 season can be predicted with reasonable accuracy. A search of the SkyMorph database of NEAT observations shows that high-quality images were obtained surrounding the predicted location of our object from the Samuel Oschin Telescope on the nights of 2002 October 9 and 29. The two orbital prediction methods described above predict positions separated by $8''.5$, although the BK2000 method suggests an error ellipse of semimajor axis only $4''.2$. This positional discrepancy is caused by an energy constraint in the BK2000 method that breaks degeneracies in short-arc orbits by preferring lower energy, less eccentric orbits. The least-squares method, with no such constraint, finds a more eccentric orbit and therefore a slightly different position. We estimate an error ellipse for the least-squares method by a Monte Carlo method in which we add $0''.3$ errors to our observations and recalculate an orbit and predicted position.

Figure 2 shows the 2002 October 29 NEAT data with both predictions and error ellipses. A single unique detection of the right magnitude appears within the full $5' \times 5'$ field shown, and this detection is well within the error ellipse of the more eccentric least-squares orbital fit. The probability of the single unique detection randomly falling within either error ellipse is 5×10^{-4}. Including this detection in our fit breaks the orbital degeneracy, and now the BK2000 and least-squares methods find essentially the same orbit and same errors. With the inclusion of the October 29 point, the error for 2002 October 9 shrinks to less than an arcsecond. Again, the only proper magnitude unique detection within a $5' \times 5'$ area appears at precisely this location, and we are confident that we have detected Sedna.

Extension of the orbit to 2001 yields additional potential detections from the NEAT survey on October 24 and September 26. The October 24 error ellipse is $2''.1 \times 0''.7$, and a unique detection of the correct magnitude appears within this small area. The data quality in 2001 is not as high as the previous data, and this detection is near the limit of the images. Consequently, the $5' \times 5'$ surrounding area contains three additional unique detections of approximately the same magnitude. Nonetheless, the probability is only 1.5×10^{-3} of one of these random unique detections falling within our small error ellipse. The September 26 data contain a unique detection at precisely the right location, but also three other comparable unique detections within $5'$. The random probability is less than 10^{-3}. We conclude that both 2001 images indeed show our object.

Attempting to propagate the orbit to 2000 or earlier results in several potential detections, but the data quality are sufficiently low that we deem the probability of coincidence too high to consider these. A special attempt was made to find the object in 1991 September Palomar Digitized Sky Survey images where the error ellipse is still only $26''.7 \times 1''.1$, and while a unique detection can be found within the error ellipse, we find many potentially spurious unique detections at the same level and determine the probability for such a random detection to be as high as ~3%, so we discount this candidate early detection as unreliable.

3. ORBITAL SOLUTION

The best-fit BK2000 orbit for the full set of 2001–2003 data yields a current heliocentric distance r of 90.32 ± 0.02, a semimajor axis a of 480 ± 40 AU, an eccentricity e of 0.84 ± 0.01, and an inclination i of 11.927. The object reaches perihelion at a distance of 76 AU on 2075 September 22 ± 260 days. The rms residuals to the best-fit error are $0''.4$ with a maximum of $0''.6$, consistent with the measurement error of the positions of these objects. The full least-squares method gives results within these error bars.

The heliocentric distance of 90 AU, consistent with the simple estimate from the night of discovery, is more distant than anything previously observed in the solar system. Many known Kuiper Belt objects and comets travel on high-eccentricity orbits out to that distance and beyond, so detection of a distant object is not inconsistent with our present understanding of the solar system. The distant perihelion is, however, unanticipated. The most distant perihelion distance of any well-known solar system object is 46.6 AU for the Kuiper Belt object 1999 CL 119. To verify the robustness of the distant perihelion for Sedna, we recomputed 200 orbits while randomly adding $0''.8$ of noise (twice the rms residuals) to each of the astrometric observations and find that the derived perihelion remains within the range 73–80 AU.

4. ORIGIN

The orbit of this object is unlike any other known in the solar system. It resembles a scattered Kuiper Belt object, but with a perihelion much higher than can be explained by scattering from any known planet. The only mechanism for placing the object into this orbit requires either perturbation by planets yet to be seen in the solar system or forces beyond the solar system.

4.1. *Scattering by Unseen Planet*

Scattered Kuiper Belt objects acquire their high eccentricities through gravitational interaction with the giant planets. Such scattering results in a random walk in energy and thus semimajor axis, but only a small change in perihelion distance. Scattering by Neptune is thought to be able to move an object's perihelion only out to distances of ~36 AU (Gladman et al. 2002), although more complicated interactions including migration can occasionally raise perihelia as high as ~50 AU (Gomes 2003), sufficient to explain all of the known Kuiper Belt objects. Our object could not be scattered into an orbit with a perihelion distance of 76 AU by any of the major planets. An alternative, however, is the existence of an undiscovered approximately Earth mass planet at a distance of ~70 AU that scattered the object just as Neptune scatters the

Kuiper Belt objects. Hogg et al. (1991) place dynamical limits the existence of such a planet and show that a planet at 70 AU of approximately 2 $M_\oplus$ should cause detectable modifications of the orbits of the giant planets, but no dynamical constraints exist on smaller objects. Nonetheless, our current survey has covered at least 80% of the area within 5° of the ecliptic—where such a planet would be most expected—with no planetary detections (Trujillo & Brown 2003). We therefore deem the existence of such a scattering planet unlikely, but we are unable to rule the possibility out completely.

Nonetheless, if such a planet does indeed exist—or did exist at one time—its signature will be unmistakable in the orbital parameters of all additional new objects detected in this region. All should have modest inclinations and perihelion similar to the 76 AU perihelion found here.

4.2. *Single Stellar Encounter*

This unusual orbit resembles in many ways one expected for a comet in the Oort Cloud. Oort Cloud comets are thought to originate in the regular solar system, where they suffered encounters with giant planets that scatter them into highly elliptical orbits. When these eccentric orbits take the comets sufficiently far from the Sun, random gravitational perturbations from passing stars and from Galactic tides modify the orbit, allowing the perihelion distance to wander and potentially become decoupled from the regular planetary system. Calculations including the current expected flux of stellar encounters and Galactic tides show that a comet must reach a semimajor axis of $\sim 10^4$ AU before these external forces become important (Oort 1950; Fernandez 1997). Once comets obtain such a large semimajor axis the orbits become essentially thermalized, with mean eccentricities of $\frac{2}{3}$ and isotropic inclinations. Continued perturbations can move the perihelion back into the planetary region, where the object becomes a new visible comet with a semimajor axis still $\sim 10^4$ AU.

The major inconsistency between this picture of the formation of the Oort Cloud and the orbit of our newly discovered object is the relatively small semimajor axis of the new object compared to the distance at which forces outside of the solar system should allow significant perihelion modification. Calculations show that a body with a semimajor axis of 480 AU and a perihelion in the planetary region should have had its perihelion modified by $\lesssim 0.3\%$ over its lifetime due to external forces (Fernandez 1997). Perihelion modification of such a tightly bound orbit requires a stellar encounter much closer than expected in the solar system's current Galactic environment.

Only a small range of encounter geometries are capable of perturbing a scattered Kuiper Belt–like orbit to this more Oort Cloud–like orbit. As an example, simple orbital integrations show that an encounter of a solar mass star moving at 30 km s^{-1} perpendicular to the ecliptic at a distance of 500 AU will perturb an orbit with a perihelion of ~ 30 AU and semimajor axis of ~ 480 AU to one with a perihelion of 76 AU, like that seen. The need for a special geometry is not surprising, since any single stellar encounter would have a geometry that is unique. More difficult to explain, however, is that fact that in the present stellar environment, the probability of even one encounter the solar system is only about 20% (Fernandez 1997). If the population of objects on large scattered orbits were in steady state the rarity of such an encounter would matter less, since the encounter could occur any time in the past 4.5 billion years. In reality, however, the number of highly elliptical orbits capable of being perturbed into the inner Oort Cloud must have been significantly higher very early in the history of the solar system when the outer solar system was being cleared of icy planetesimals and the Oort Cloud was being populated. The probability of a random close stellar encounter so early is improbable.

Nonetheless, if such a stellar encounter did indeed occur, its signature will be unmistakable in the orbital parameters of all subsequent objects found in this region. If all of the objects found in this inner Oort Cloud region are consistent with the same unique stellar encounter geometry, it will be clear that we are seeing the fossilized signature of this encounter.

4.3. *Formation in a Stellar Cluster*

Close encounters with stars would have been more frequent early in the history of the solar system if the Sun had formed inside a stellar cluster. In addition, these encounters would have been at much slower speeds, leading to larger dynamical effects. In numerical simulations, Fernandez & Brunini (2000) found that early multiple slow moderately close encounters are capable of perturbing objects into orbits such as the one here. The process is identical to that hypothesized for the creation of the more distant Oort Cloud, but in a denser environment the comets do not need to have as large of a semimajor axis before they are perturbed by the stronger external forces. Fernandez & Brunini predict that a population of objects with semimajor axes between $\sim 10^2$ and $\sim 10^3$ AU, perihelia between ~ 50 and $\sim 10^3$ AU, large eccentricities (mean ~ 0.8), and a large inclination distribution (a FWHM of $\sim 90°$) in this inner region of the Oort Cloud formed in an early dense stellar environment.

The inclination of Sedna appears unusually small compared to the large expected inclination distribution of such an inner Oort Cloud population. However, an observational bias exists for detecting objects with inclinations similar to the ecliptic latitude of the observation. In our observations, Sedna was discovered at an ecliptic latitude of 11°.9 and has a measured inclination of 11°.9. The probability that an object found at 12° latitude has an inclination of less than 13° if the object is drawn from a widely distributed population like that predicted by Fernandez & Brunini is ~10%. A third of all objects at 12° will have inclinations smaller than 20°. We thus do not find the small inclination of Sedna to be inconsistent with the distribution expected in this inner Oort Cloud scenario.

We currently regard this scenario as the most likely for the creation of the unusual orbit of our newly discovered object. Formation of the solar system in a stellar cluster is a reasonable expectation (Clarke et al. 2000) for which potential evidence exists from other contexts (Goswami & Vanhala 2000). If indeed this scenario is correct, the orbits of any newly discovered objects in this region will unmistakably reflect this early history. The new discoveries will be widely spread in inclination and perihelion and will not be consistent with any special single stellar encounter geometry. As seen in the simulations of Fernandez & Brunini, the precise distribution of orbits in this inner Oort Cloud will be indicative of the size of this initial cluster.

It is possible that a second such object is known already (or perhaps more). The scattered Kuiper Belt object 2000 CR 105 has a perihelion distance of 44 AU and a semimajor axis of 227 AU. Its present orbital configuration can be fully explained by a complex path involving migration of Neptune, scattering, and resonances (Gomes 2003), so its existence does not require any external forces. However, the cluster formation scenario naturally leads to orbits such as that of 2000 CR 105. The relatively small perihelion change of 2000 CR 105 in this scenario is thus consistent with the relatively modest semimajor axis of the object. Unfortunately, 2000 CR 105 is close enough to the planetary region that it has possibly suffered enough interaction to change its orbital parameters to erase the clear dynamical signatures we seek in this population.

5. DISCUSSION

Each of the plausible scenarios for the origin of the distant object predicts a specific dynamical population beyond the Kuiper Belt. With only a single object, though, little dynamical evidence exists for preferring any one scenario. With any new discoveries in this region, evidence should quickly mount.

We can make a simple order-of-magnitude estimate of the ease of future discovery of objects in this population. We find a single distant object in our survey, while we have discovered 40 Kuiper Belt objects to date in the survey. Assuming the size distribution of the distant population is the same as that of the Kuiper Belt, other surveys should find similar proportions, assuming they are equally sensitive to slow motions. As of 2004 March 15, 831 minor planets have been detected beyond Neptune; we thus expect to have seen ~20 similar objects from other surveys. Even with this rough estimate, the lack of previous detections appears significant, suggesting either that most surveys have not been sensitive to motions as slow as $\sim 1''.5$ hr^{-1} or that there is an overabundance of comparatively bright objects in the distant population. In either case, it appears likely that new objects in this population should be detected reasonably soon.

The most plausible scenario for the origin of our object appears to be the dynamical effect of the creation of the solar system within a dense stellar cluster. In this scenario the Oort Cloud extends from its expected location at ~100,000 AU all the way in to the location of Sedna. If this scenario is indeed correct, the total mass of the Oort Cloud must be many times higher than previously suspected. The expected population of large objects like the one discovered here is large. Our survey could only have detected this object during ~1% of its orbit, suggesting a population of ~100 objects on similar orbits. Moreover, if the population is nearly isotropic, ~five more such objects must be observable in the current sky, with a total population of 500. Assuming a size distribution similar to the Kuiper Belt, the total mass of this population is $\sim 5\ M_{\oplus}$. The unseen population with ever more distant perihelia are likely even more numerous. With only the single object known in this population, extrapolation of a precise mass is not possible; nonetheless, the existence of a nearby massive previously unsuspected inner Oort Cloud appears likely. Even in the other origin scenarios a significant new mass must likely be present. At these distances, and in particular for isotropic distributions, current dynamical methods are unable to rule out any reasonable population (Hogg et al. 1991). If the distant populations are sufficiently large, however, they may be detectable in future occultation surveys.

While the genesis of Sedna is currently uncertain, continued discovery and orbital characterization of similar high-perihelion objects should allow a unique and straightforward interpretation of this population. Each hypothesized formation mechanism leads to the prediction of a different dynamically distinct population in the outer solar system. Study of these populations will lead to a new knowledge of the earliest history of the formation of the solar system.

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