DISCOVERY OF A LOW-ECCENTRICITY, HIGH-INCLINATION KUIPER BELT OBJECT AT 58 AU

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ABSTRACT

We report the discovery of the first trans-Neptunian object, designated 2004 XR₁₉₀, with a low-eccentricity orbit beyond the 2 : 1 mean motion resonance. Fitting an orbit to 23 astrometric observations spread out over 12 months yields an orbit of $a = 57.2 \pm 0.4$, $e = 0.08 \pm 0.04$, and i = 46°.6. All viable orbits have perihelia distances q > 49 AU. The very high orbital inclination of this extended scattered disk object might be explained by several models, but its existence again points to a large as-yet undiscovered population of trans-Neptunian objects with large orbital perihelia and inclination.

Subject headings: Kuiper Belt — solar system: formation

1. INTRODUCTION

Over the last decade, serious observational effort has gone into detecting trans-Neptunian objects (TNOs), but despite increasing resources dedicated to the problem there is still a steady stream of surprises. So little light is reflected from distant TNOs that it is the very inner edge (within 50 AU) of the Kuiper Belt region that dominates detections in observational surveys (those with more than 10 detections include Jewitt et al. 1996; Trujillo et al. 2001; Larsen et al. 2001; Gladman et al. 2001; Allen et al. 2002, 2005; Elliot et al. 2005; Petit et al. 2005). The majority of Kuiper Belt detections come from these flux-limited surveys near the ecliptic plane. This results in a bias against objects that are distant (since reflected flux is proportional to d^{-4}), on highly inclined orbits (which spend very little time in the ecliptic plane), or intrinsically rare (like the very largest TNOs). These biases are gradually being overcome, and new dynamical classes within the Kuiper Belt are being discovered.

These subpopulations of the Kuiper Belt (see Gladman [2005] for a recent review) preserve a record of the dynamical processes that governed the formation of the giant planets. The low-eccentricity "classical belt" appears to decline rapidly at the location of the 2:1 mean motion resonance (Allen et al. 2001; Trujillo & Brown 2001) Other mean motion resonances are occupied both inside and outside the 2:1, although those objects outside the 2:1 are only present at high eccentricity (with the possible exception of 2004 XR_{190}). The scattered disk population of TNOs has perihelia q < 40 AU but large semimajor axes *a*; this is a decaying population that has presumably been flung to large a via scattering with Neptune (Duncan & Levison 1997). Finally, the extended scattered disk (which eventually merges into the inner Oort Cloud) consists of TNOs on stable orbits, pointing to some process capable of lowering the orbital eccentricities of vast numbers of scattered disk objects (Gladman et al. 2002; Brown et al. 2004). In this Letter we report the discovery of a new extended scattered-disk object with a low-eccentricity orbit beyond the edge of the classical belt and also with one of the highest orbital inclinations known.

2. OBSERVATIONS

The object reported here was discovered in routine data reduction of the Canada-France Ecliptic Plane Survey (Allen et al. 2005). The internal survey designation was 0716p004b7, and it has received Minor Planet Center designation 2004 XR₁₉₀ (Kavelaars et al. 2005). In this section, we describe the discovery and tracking observations up to 2005 December 10.

2.1. Discovery

2004 XR₁₉₀ was discovered in images taken as part of the Canada-France Legacy Survey using data from the Very-Wide component (CFLS-VW) on the Canada-France-Hawaii Telescope (CFHT) 3.5 m and Megacam CCD camera. The images were processed by CFHT using their Elixir data processing pipeline (Magnier & Cuillandre 2004) and then searched for TNOs with our moving-object software (Petit et al. 2004). 2004 XR₁₉₀ was clearly identified by the software, being about 2 mag above the limit and uncontaminated by background objects. A fourth image, taken on the following night, gave a preliminary orbit indicating the object's distance was well beyond 50 AU. These exposures were taken on 2004, December 11 and 12, using an *r*-filter and 90 s exposure times. 2004 XR₁₉₀ was measured to have an *r*-magnitude of 21.8 \pm 0.2 in these short exposures.

Astrometry of 2004 XR₁₉₀ from the discovery images indicated that it was at a barycentric distance of 59 ± 5 AU when an orbital solution was fit using the Bernstein & Khushalani (2000) software. This indicates its diameter is between 425 and 850 km for a range of albedo of 16%–4%.

Although orbital elements are poorly constrained with only a 24 hr arc, because the observations were taken at opposition, the distance estimate from two nights of observation was felt to



FIG. 1.—Coupled uncertainties in semimajor axis and eccentricity for 2004 XR_{190} . The best-fit orbital elements are shown by a filled circle. The small points show orbital solutions consistent with our astrometric data to a 0".5 mean-residual level. The distribution of these points illustrates the correlation between *a* and *e* and may be considered an uncertainty ellipse for these parameters. The box shows the 1 σ uncertainties in *a* and *e* returned by the Bernstein & Khushalani (2000) software (stated in the text), but this ignores the *a/e* correlation. The dashed line indicates the center of the 8 : 3 mean motion resonance at 57.8 AU. Dotted curves are loci of constant perihelion. 2004 XR_{190} 's best-fit perihelion distance is at 51.4 AU.

be accurate to 10%. Even with the uncertainty, this made 2004 XR₁₉₀ one of the most distant TNOs ever discovered. Much more uncertain at the time, but even more exciting, was the fact that its preliminary orbit indicated that $a = 59 \pm 30$ AU, $e = 0.02 \pm 0.5$, and $i = 45^{\circ}(\pm 24^{\circ})$. The unusual nature of this orbit and the large barycentric distance led us to follow this object at the next opportunity in 2005.

2.2. Tracking

On 2005 October 3 and 4, a first set of recovery observations was obtained at the Palomar 5 m using the Large-Format Camera. Observations taken 1 yr after a 24 hr arc generally have a very large ephemeris uncertainty (Allen et al. 2005), around 27' in this case. However, 2004 XR₁₉₀ was immediately visible in the field within 1" of the prediction from the nominal nearly circular orbit. Incorporating the new astrometric measurements indicated that the distance was indeed 58.6 \pm 0.3 AU, although the best-fit orbit became more eccentric with a higher a $(a = 63 \pm 28 \text{ AU}, e = 0.3 \pm 0.7)$. This recovery also confirmed that 2004 XR₁₉₀ had one of the largest orbital inclinations of any TNO (then $i = 46^{\circ}.1 \pm 0^{\circ}.4$); only one other classical Kuiper Belt object and one scattered disk object have higher inclinations. This pattern of orbits changing from near-circular to elliptical often emerges when fitting increasing arc lengths with the Bernstein & Khushalani (2000) code, as the orbit assumptions are changed as the observational arc grows. However, the uncertainties remain large and the final orbit remains within these limits.

Further observations took place in 2005, at the MDM 2.4 m on October 15, at the Kitt Peak Mayall 4 m on November 4 and 6, and again at CFHT on December 1. Although these observations only increased the arc length from 10 to 12 months, because of



FIG. 2.—Points show well-determined orbits for Kuiper Belt objects in semimajor axis vs. eccentricity and semimajor axis vs. inclination space. 2004 XR_{190} 's current best-fit orbit is indicated by a triangle with error bars for *a* and *eli*. Objects from the Minor Planet Center database with an observational arc of over two oppositions are indicated by dots. Dashed curves on the semimajor axis vs. eccentricity plot indicate perihelion distances of 30, 40 and 50 AU.

the spread of the observational geometry relative to opposition, orbital-element uncertainties dropped very rapidly. Including all available observations, we find the best-fit orbit to be $a = 57.5 \pm 0.6$ AU, $e = 0.11 \pm 0.04$, and $i = 46^{\circ}.641 \pm 0^{\circ}.005$, with node = 252°.367, argument of perihelion 284° ± 6°, and time of perihelion passage of JD = 2,494,000 ± 3000.

While the large current barycentric distance of 58.43 ± 0.03 AU and high inclination are unusual, a third, and probably most important, feature of this orbit is its large pericentric distance. The uncertainties quoted above in *a* and *e* are correlated; increases in *e* necessitate an increase in *a* to continue to fit the observations, as illustrated in Figure 1. As such, the limits on *q* are stricter than the simple 1 σ limits above. Taking into account this correlation, we find that the lowest possible *q* compatible with the observations, at the 1 σ level, is in fact 49.4 AU. This places 2004 XR₁₉₀ in the extended scattered disk, although its eccentricity is the lowest of any member of this group.

3. DISCUSSION

2004 XR₁₉₀ is unlike any other member of the Kuiper Belt, due to its high pericenter and highly inclined orbit, as illustrated in Figure 2. With a fairly circular orbit beyond 50 AU, it would be tempting to think of this object as the first member of a "cold distant belt" (see Stern & Colwell 1997; Hahn & Malhotra 1999). However, its high inclination suggests that it has experienced a strong dynamical perturbation in its history.

We discovered 2004 XR_{190} only ~1° away from the ecliptic plane. With $i = 47^{\circ}$, it spends only a tiny fraction (~2%) of its orbit within this limit. Most TNO surveys do not extend farther than a few degrees from the ecliptic plane and thus have poor sensitivity to TNOs on such high-i orbits. The ongoing Caltech Survey (Trujillo & Brown 2003) has covered a major fraction of the sky within 10° of the ecliptic and is increasing coverage farther away. The limit of this survey is in the range $m_R \sim$ 20-21, such that objects must be on the order of 1000 km in diameter to be detected beyond a distance of 60 AU. With these selection effects, we cannot rule out a large population of high*i* objects like 2004 XR_{190} . However, a population with similar *a* and e but low-i should have been undetected in prior surveys. Indeed, Allen et al. (2002) and Trujillo & Brown (2001) set strong limits on such a distant "cold belt." Therefore, we conclude that 2004 XR_{190} does not represent the high-inclination end of a dynamically cold population beyond 50 AU. More likely is that this discovery is a member of an as-yet poorly characterized very high-*i* group. Because of the presence of other very highly inclined TNOs in the classical belt and the scattered disk, it is unclear whether the highest inclination population is especially concentrated in the extended scattered disk or extends throughout the Kuiper Belt.

Placing a TNO onto a nearly circular orbit near 60 AU with a high inclination while simultaneously leaving intact the inner Kuiper Belt and depopulating the low-inclination orbits beyond the 2 : 1 resonance, is a challenge for theories attempting to create the extended scattered disk. These theories include close stellar passages, rogue planets/planetary embryos in the early Kuiper Belt, and resonance interaction with a migrating Neptune.

In stellar passage models, a star has a close encounter with the primordial Kuiper Belt or scattered disk. The end result of these encounters is a Kuiper Belt that transitions from a slightly perturbed to a greatly perturbed state beyond some critical distance (Ida et al. 2000; Kenvon & Bromley 2004; Morbidelli & Levison 2004; Kobayashi et al. 2005). Generally, objects produced with high inclination in these models also have high eccentricities, which make it difficult to produce 2004 XR_{190} . Typically the stellar passage scenarios leave behind an extended scattered disk in which the mean inclination of the extended scattered disk objects (ESDOs) rises as one moves to larger semimajor axes. With the addition of 2004 XR_{190} to the suite of ESDOs 1995 TL₈, 2000 YW₁₃₄, 2000 CR₁₀₅, and 2003 VB₁₂/ Sedna (Gladman et al. 2002; Morbidelli et al. 2004), the current trend appears to be the opposite. While the lower a ESDOs should indeed be detected in greater numbers first (due to distance/flux detection biases), the lack of high-*i* ESDOs with a > 100 AU might be viewed as a problem for stellar passage models.

Recent simulations by Gladman & Chan (2006) show that a 1–2 M_{\oplus} rogue planet living temporarily in the scattered disk can effectively create high-*q* ESDOs. Production of objects with orbital inclinations above 40° is possible but not efficient, and the high-*i* objects that are created tend to be at the lowest semimajor axes (*a* < 100 AU). If TNOs with orbital inclinations above 30° are discovered beyond *a* = 100 AU, then a stellar passage scenario should indeed be favored. If this method did produce 2004 XR₁₉₀, *a* ~ 100 AU, *e* ~ 0.5 TNOs should soon be discovered with inclinations between 10° and 40°.

An intriguing explanation is that 2004 XR_{190} evolved to its current orbit after being trapped in a mean motion resonance with Neptune while Neptune migrated outward. In this model,

TNOs are trapped into resonance and evolve onto higher semimajor axis orbits as Neptune migrates outward, increasing their eccentricities in the process (Hahn & Malhotra 2005). This process is inefficient at increasing orbital inclinations to large values if the trapped objects begin on circular orbits. However, a similar effect can occur if already eccentric TNOs become trapped in the resonance during Neptune's migration. This can result in inclination pumping, primarily due to the Kozai resonance. Although weak in the Kuiper Belt outside of mean motion resonances, inside or near the edges of these resonances the Kozai effect is capable of transferring the orbital eccentricity into an elevated inclination (Gomes 2003; Gomes et al. 2005). If the object then drops out of the resonance, it will be left on a high*i*, low-*e* orbit relatively stable against the gravitational perturbations of Neptune and the other giant planets. This could explain 2004 XR_{190} 's orbit, without requiring low-*i* objects of similar semimajor axis. Gomes et al. (2005) show an example of this process using the 5 : 2 mean motion resonance, but this resonance is interior to the best-estimate semimajor axis of 2004 XR₁₉₀, so use of the 5:2 resonance to produce the orbit would require a final inward migration of Neptune. This is not impossible, as Gomes et al. (2004) show that both inward and outward Neptune migration can occur. 2004 XR₁₉₀'s best-fit orbit is in fact closer to the 8 : 3 than the 5 : 2 mean motion resonance. Unfortunately, the ability of the 8 : 3 resonance to participate in this mechanism has not been demonstrated. No published numerical models appear to exhibit trapping and strong inclination pumping in the 8:3 resonance.

We have conducted preliminary orbital integrations of a suite of particles consistent with the 1 σ uncertainties of 2004 XR₁₉₀'s orbital elements. We integrated 100 clones for 10⁷ yr. The vast majority of these clones show small (~ 0.01) variations in eccentricity over this time period. However, given the current uncertainties in the orbit, we find that there is a roughly 5% chance (see Fig. 1) that XR_{190} has orbital elements that would allow it to be strongly influenced by the 8:3 resonance. The resonant particles (as diagnosed by libration of the angle $\phi = 8\lambda - 3\lambda_N - 3\lambda_N$ $5\tilde{\omega}$ during the integrations) show an extremely strong Kozai response that brings the perihelia down into the scattered disk region (q < 38 AU) within 10^7 yr. We extended the integration of the resonant clones to 10^8 yr. The behavior of one of these resonant particles is illustrated in Figure 3; in this case the particle actually crosses Neptune's orbit after 80 Myr. We have confirmed that e, *i*, and ω show the correct coupled Kozai behavior. This raises the possibility, if future observations result in a resonant orbit, that XR_{190} is only temporarily resident in the low-eccentricity domain. In this scenario, 2004 XR₁₉₀ could have recently (as little as a few tens of millions of years ago) been a scattered disk object, which is simply undergoing a low-eccentricity episode by virtue of having been fortuitously near the resonance boundary after a Neptunescattering event. The dynamics of this near-resonance should be further explored if observations in early 2006 confirm that a and e are both at the high end of the currently allowed range. Even if future observations show 2004 XR_{190} has a value of *a* just below that of the resonance (as the current best-fit orbit indicates), the strong resonant response seen in our integrations does suggest the possibility that a "resonant drop-off" mechanism could have delivered it to its current location.

4. CONCLUSION

We have presented the discovery of an unusual TNO, 2004 XR_{190} , with a perihelion at ~50 AU, and a low-eccentricity orbit. The high inclination of 47° indicates 2004 XR_{190} has



FIG. 3.—Evolution of a clone interacting with the 8:3 resonance. The particle's initial orbital elements are within 2004 XR_{190} 's orbital uncertainties but place it near the resonance. This particle undergoes Kozai pumping of its eccentricity such that its perihelion distance periodically drops below 35 AU and during the third eccentricity minimum interacts strongly with Neptune and is removed from near the resonance. The solid curves indicate semimajor axis (*a*) and perihelion (*q*).The dashed curve indicates the inclination (*i*) history, which is in phase with the *q* history due to the Kozai effect. Neptune's semimajor axis throughout the simulation is indicated by the dotted curve.

clearly been dynamically perturbed at some point in its lifetime and is difficult to reconcile with an eccentricity of e = 0.11.

A plausible explanation of the origin of 2004 XR_{190} 's high inclination and low eccentricity is the action of the Kozai effect during a past residence inside the 5 : 2 or 8 : 3 mean motion

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resonances of Neptune. If Neptune migrated outward, dropping the TNO out of resonance, this could aid in freezing the *e/i* combination observed today. The modification of its orbit could also be produced by now-absent bodies (rogue planets or passing stars), but producing all of the features present in the trans-Neptunian region is problematic for all of the above models.

This Letter would not be possible without observations obtained at a number of telescopes. Based on observations obtained with MegaPrime/Megacam, a joint project of CFHT and CAE/DAPNIA, at the CFHT, which is operated by the National Research Council (NRC) of Canada, the Institut National des Science de l'Univers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii. This work is based in part on data products produced at TER-APIX and the Canadian Astronomy Data Centre (CADC) as part of the Canada-France-Hawaii Telescope Legacy Survey, a collaborative project of NRC and CNRS. Also based partly on observations obtained at the Hale Telescope, Palomar Observatory, as part of a collaborative agreement between the California Institute of Technology, its divisions Caltech Optical Observatories and the Jet Propulsion Laboratory (operated for NASA), and Cornell University. Additional observations from Kitt Peak National Observatory, National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation. We would also like to thank Arlin Crotts and Patrick Cseresnjes, Columbia University, for their help in obtaining images of 2004 XR₁₉₀. R. L. A. and B. G. acknowledge support from NSERC and CFI. J. Wm. P. acknowledges support by NASA Planetary Astronomy Program grant NNG04GI29G.

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