



BEYOND THE KUIPER BELT EDGE: NEW HIGH PERIHELION TRANS-NEPTUNIAN OBJECTS WITH MODERATE SEMIMAJOR AXES AND ECCENTRICITIES

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ABSTRACT

We are conducting a survey for distant solar system objects beyond the Kuiper Belt edge (~ 50 au) with new wide-field cameras on the Subaru and CTIO telescopes. We are interested in the orbits of objects that are decoupled from the giant planet region to understand the structure of the outer solar system, including whether a massive planet exists beyond a few hundred astronomical units as first reported in 2014 by Trujillo & Sheppard. In addition to discovering extreme trans-Neptunian objects detailed elsewhere, we found several objects with high perihelia ($q > 40$ au) that differ from the extreme and inner Oort cloud objects due to their moderate semimajor axes ($50 < a < 100$ au) and eccentricities ($e \lesssim 0.3$). Newly discovered objects 2014 FZ71 and 2015 FJ345 have the third and fourth highest perihelia known after Sedna and 2012 VP113, yet their orbits are not nearly as eccentric or distant. We found several of these high-perihelion but moderate orbit objects and observe that they are mostly near Neptune mean motion resonances (MMRs) and have significant inclinations ($i > 20^\circ$). These moderate objects likely obtained their unusual orbits through combined interactions with Neptune's MMRs and the Kozai resonance, similar to the origin scenarios for 2004 XR190. We also find the distant 2008 ST291 has likely been modified by the MMR+KR mechanism through the 6:1 Neptune resonance. We discuss these moderately eccentric distant objects along with some other interesting low inclination outer classical belt objects like 2012 FH84 discovered in our ongoing survey.

Key words: comets: general – Kuiper Belt: general – minor planets, asteroids: general – Oort Cloud – planets and satellites: individual (Sedna, 2012 VP113, 2004 XR190)

1. INTRODUCTION

The Kuiper Belt is composed of small icy bodies just beyond Neptune. It has been dynamically and collisionally processed (Morbidelli et al. 2008, pp. 275–292; Petit et al. 2011). Much of the structure of the Kuiper Belt can be explained through interactions with Neptune (Dawson & Murray-Clay 2012; Nesvorný 2015a, 2015b; Nesvorný & Vokrouhlický 2016). The Neptune resonant objects were likely emplaced by Neptune's outward migration (Malhotra 1995; Gomes et al. 2005; Gladman et al. 2012; Sheppard 2012). The scattered objects not in resonance have large eccentricities with perihelia near Neptune ($q < 38$ au), suggesting strong interactions with the planet (Gomes et al. 2008, pp. 259–273; Brasil et al. 2014b). Extreme trans-Neptunian (ETNOs) or inner Oort cloud objects have high perihelia ($q > 40$ au), large semimajor axes ($a > 150$ au) and large eccentricities (Gladman et al. 2002; Brown et al. 2004; Morbidelli & Levison 2004; Gomes et al. 2005, 2006; Trujillo & Sheppard 2014). These extreme objects are currently decoupled from the giant planets, but must have interacted with something in the past to obtain their extreme orbits (Kenyon & Bromley 2004; Gladman & Chan 2006; Schwamb et al. 2010; Brasser et al. 2012; Soares & Gomes 2013). The similarity in the extreme objects' orbital angles suggests they are being shepherded by an unseen massive distant planet (Trujillo & Sheppard 2014; Batygin & Brown 2016). There is an edge to the Kuiper Belt for low to

moderately eccentric objects around 48 au (Jewitt et al. 1998; Trujillo & Brown 2001; Allen et al. 2002).

Early dynamical simulations showed that objects scattered by Neptune could obtain high perihelia, moderately eccentric orbits from Neptune interactions (Torbett & Smoluchowski 1990; Holman & Wisdom 1993; Malhotra 1995). Until now, only one object, 2004 XR190, was known to have a perihelion significantly beyond the Kuiper Belt edge, yet only have a moderate eccentricity and moderate semimajor axis (Allen et al. 2006). 2004 XR190 likely obtained its high perihelion during Neptune's outward migration, where the combined effect of the 8:3 Neptune Mean Motion Resonance (MMR) along with the Kozai Resonance (KR) modified the eccentricity and inclination of 2004 XR190 to obtain a very high perihelion (Gomes et al. 2008, pp. 259–273; Gomes 2011). The MMR+KR high-perihelion objects may allow insights into the past migrational history of Neptune. In this Letter, we report several new high-perihelion objects ($q > 40$ au) that have only moderate eccentricities ($e \lesssim 0.3$) and semimajor axes ($50 < a < 100$ au), showing that a significant population of these objects exist. This work is part of our ongoing survey. Here, we focus on the moderate objects found beyond the Kuiper Belt edge.

2. OBSERVATIONS

Basic methodology of the survey have been published in Trujillo & Sheppard (2014) and further details will be published elsewhere (S. Sheppard & C. Trujillo 2016, in preparation). The majority of the area surveyed was with the CTIO 4 m Blanco telescope in Chile with the 2.7 square degree

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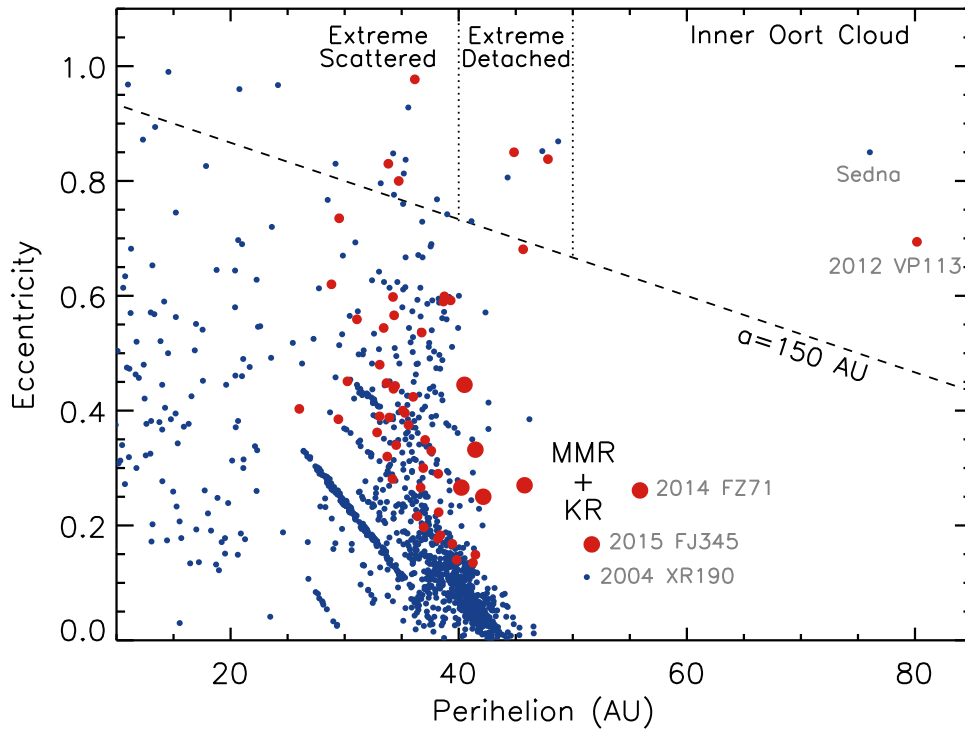


Figure 1. Perihelion vs. eccentricity. The red circles are objects discovered during this survey (the large red circles are the focus of this work). Objects above the dashed line are considered extreme with $a > 150$ au. Objects with high perihelia beyond the Kuiper Belt edge at 50 au but only moderate eccentricity are likely created by a combination of Neptune Mean Motion Resonances (MMR) and the Kozai Resonance (KR).

Dark Energy Camera (DECam). DECam has 62 2048×4096 pixel CCD chips with a scale of 0.26 arcsec per pixel (Flaugher et al. 2015). The r -band filter was used during the early observing runs (2012 November and December and 2013 March, May, and November), reaching to about 24th magnitude while the wide VR filter was used in the later observations (2014 March and September and 2015 April) to about 24.5 mag. In addition, we have used the Subaru 8 m telescope in Hawaii with its 1.5 square degree HyperSuprime-Cam. HyperSuprimeCam has 110 CCD chips with scale of 0.17 arcsec per pixel. The observations were obtained in 2015 March and May to just over 25th magnitude in the r -band. We covered 1078 and 72 square degrees at CTIO and Subaru, respectively, for a total of 1150 square degrees.

Most fields had three images of similar depth obtained over 3–6 hr. Observations were within 1.5 hr of opposition, which means the dominant apparent motion would be parallactic, and thus inversely related to distance. The seeing was between 0.6 and 1.2 arcsec for most fields, allowing us to detect objects moving faster than 0.28 arcsec per hour, which corresponds to about 500 au at opposition, though many fields would have detected objects to over 1000 au (determined by placing artificial slow objects in the fields). Anything discovered beyond 50 au was flagged for future recovery. Most of the survey fields were between 5° and 20° from the ecliptic with fairly uniform longitudinal coverage.

3. RESULTS

The new objects discovered in our survey are shown with the well-known outer solar system objects in Figure 1. The region of orbital space beyond 50 au in semimajor axis but with moderate to low eccentricities ($e \lesssim 0.3$) has been called the Kuiper Belt edge since only 2004 XR190 was known to occupy

this area until now. Several of our new objects have perihelia well above the generally accepted perihelion limit where Neptune has significant influence ($q > 40$ –41 au: Gomes et al. 2008, pp. 259–273; Brassier & Schwamb 2015). Though they have high perihelia, they only have moderate semimajor axes ($50 < a < 100$ au), unlike the extreme and inner Oort cloud objects with $a > 150$ au that likely have a different history and were detailed in Trujillo & Sheppard (2014). As seen in Figure 2, it appears that most of these moderate objects beyond the Kuiper Belt edge are near strong Neptune MMRs (Table 1). This suggests that these moderate orbits were created through MMR interactions.

This situation is similar to that of the high-perihelion object 2004 XR190 (Gomes 2011), although the new objects do not have exceptionally high inclinations like 2004 XR190 ($i = 46.7^\circ$). A high inclination of over 40° is required for the KR mechanism to efficiently operate and modify orbits by itself (Kozai 1962; Lidov 1962). More moderately inclined objects with inclinations of 20° – 40° can have their orbits significantly modified by the KR if they are also in a MMR (Duncan & Levison 1997; Fernandez et al. 2004). The combined MMR + KR mechanism could allow objects to obtain perihelia up to 60 au (Gomes et al. 2008, pp. 259–273).

The new objects have been observed for one to three years and thus their orbital elements are secure. We used the MERCURY numerical integrator (see the Appendix) to look at the behavior of all the new objects shown in Table 1. We found all of the new orbits to be very stable over the age of the solar system. As detailed later, we examined the resonance argument angles for signs of libration, which would indicate MMR membership (Chiang et al. 2003; Elliot et al. 2005; Gladman et al. 2008, pp. 259–273; Pike et al. 2015). But the objects only need to have been in a Neptune MMR in the past to have had

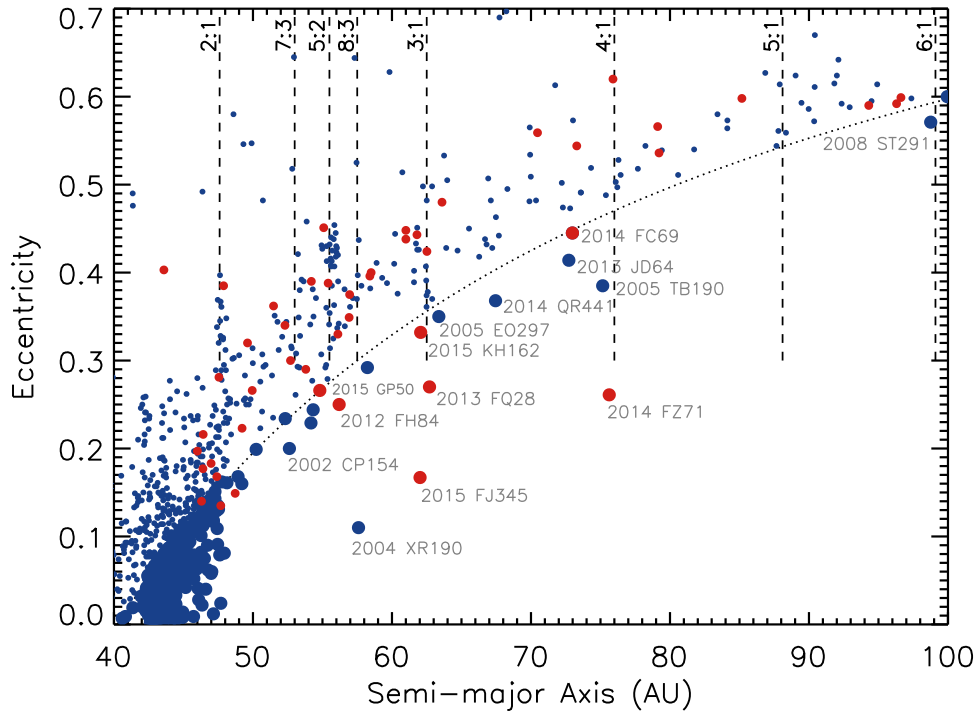


Figure 2. Semimajor axis vs. eccentricity. The red circles show the new objects discovered in this survey. The larger circles show objects with perihelia above 40 au. The dashed lines show strong mean motion resonances with Neptune. The dotted line shows a constant perihelion of 40 au. Objects to the right of the dotted line have perihelia above 40 au, and thus are mostly decoupled from Neptune. Uncertainties on the orbital parameters are smaller than the symbols.

Table 1
New High-perihelion Objects with Moderate Semimajor Axes and Eccentricities

Name	q (au)	a (au)	e	i (degree)	Ω (degree)	ω (degree)	Dist. (au)	Dia. (km)	m_r (mag)	N	$R:R$
Neptune MMR + KR											
2014 FZ71	55.9	76.4	0.268	25.440	305.85	243.7	56.8	150	24.4	12	4:1
2015 FJ345	51.8	62.5	0.17	35.00	37.88	80.4	58.5	100	25.5	13	3:1
2004 XR190	51.2	57.5	0.110	46.7	252.4	283.4	58.5	600	21.8	...	8:3
2013 FQ28	45.8	63.2	0.27	25.70	214.89	230.4	66.8	250	24.1	15	3:1
2008 ST291*	42.3	98.8	0.572	20.8	324.2	331.2	56.7	600	21.5	...	6:1
2015 KH162	41.5	62.1	0.33	28.8	200.8	296.1	58.8	800	21.1	41	3:1
2015 GP50	40.5	55.3	0.27	24.15	222.69	128.4	68.2	200	24.7	13	5:2?
2014 FC69	40.5	72.9	0.44	30.1	250.2	189.3	83.7	500	23.6	10	11:3?
Outer Classical Belt											
2012 FH84	42.7	56.4	0.24	3.62	21.37	7.2	68.1	150	25.3	9	5:2?

Note. Objects in italics were known before this work and those with an asterisk indicate a new result. Quantities are the perihelion (q), semimajor axis (a), eccentricity (e), inclination (i), longitude of the ascending node (Ω), argument of perihelion (ω), distance (Dist.), number of observations (N), and Neptune resonance ($R:R$), where ? means possible but unlikely resonant affiliation. Diameter (Dia.) assumes a moderate albedo of 0.10. Orbits are from the MPC and uncertainties are shown by the number of significant digits.

their orbits significantly modified by the MMR+KR mechanism (Gallardo 2006a). If not in but near a MMR today, the objects could have either escaped or Neptune migrated away to remove them from the MMR as suggested for 2004 XR190's orbit (Gomes 2011). Based on the Neptune MMR maps shown in Gallardo (2006b), all the new very high perihelion, moderate semimajor axis objects are near strong Neptune MMRs (Figure 2).

3.1. The Very High Perihelion of 2014 FZ71

One of the most interesting new objects is 2014 FZ71, which has the highest perihelion of any known object after Sedna and 2012 VP113 (Figure 1). However, 2014 FZ71's moderate

eccentricity and semimajor axis compared with Sedna and 2012 VP113 suggests that it has a different origin. 2014 FZ71 is very close to the 4:1 MMR with Neptune, and thus 2014 FZ71's orbit was likely modified through interactions with it. Interestingly, the large perihelion of 55.9 au suggests 2014 FZ71 would not currently have any strong interaction with Neptune. The relatively moderate inclination and eccentricity of 2014 FZ71 make it harder to invoke the Kozai mechanism for the high perihelion of 2014 FZ71. In our numerical simulations with 10 1 sigma orbit clones, we find some of the basic 4:1 resonance argument angles, called e^3 , es^2 and e^2e_N in Elliot et al. (2005), showed signs of libration in some clones. This indicates 2014 FZ71 likely still interacts with the 4:1

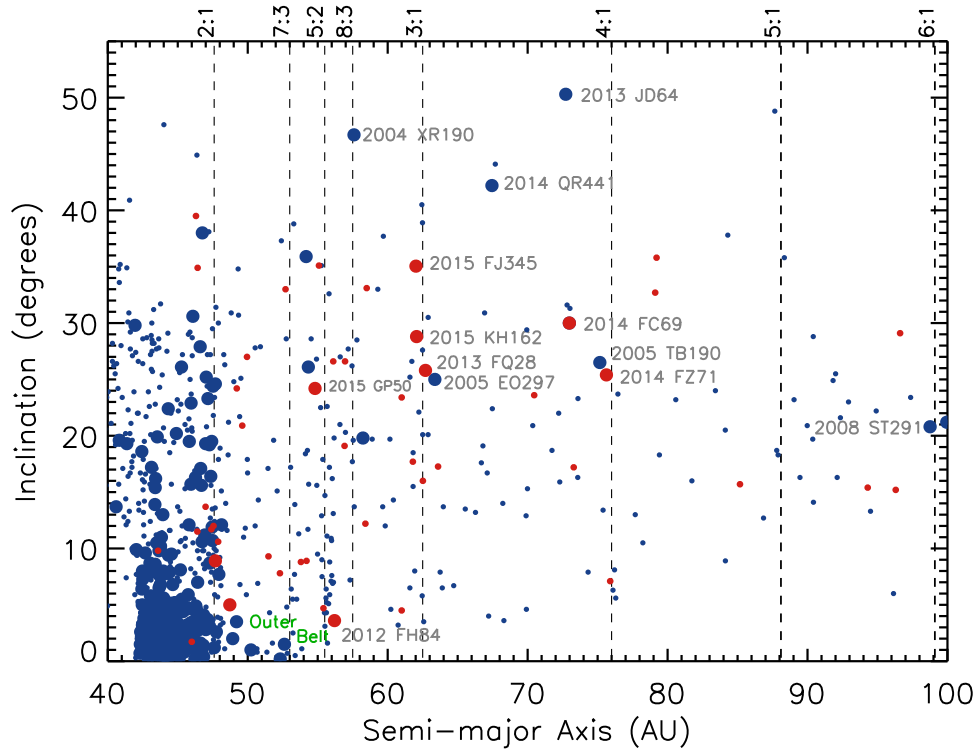


Figure 3. Similar to Figure 2, but showing inclination. The larger circles show objects that have perihelia above 40 au. All of the high-perihelion objects beyond 53 au have inclinations greater than 20° , except for our newly discovered 2012 FH84, which is likely a rare outer classical belt object along with 1995 TL8, 2002 CP154 and 2001 FL193 (the large blue circles with very low inclinations between 50 and 53 au).

Neptune MMR. We found all one sigma 2014 FZ71 clones showed constant semimajor axis but some showed large variations in i and e ($8^\circ < i < 32^\circ$ and $0.23 < e < 0.50$ giving $38 < q < 58$ au).

If 2014 FZ71 does have both the Kozai and Neptune MMR acting on it, the eccentricity of the object could vary and would be coupled to the inclination following:

$$H = \sqrt{1 - e^2} \cos(i),$$

where H is constant (Kozai 1962; Morbidelli & Thomas 1995; Gomes et al. 2008, pp. 259–273). In this formalism, the perihelion of 2014 FZ71 could have been near 38.5 au if its eccentricity was higher in the past (Figure 4). Indeed, a perihelion of around 38 au is exactly what we find as the lower perihelion limit for the librating clones of 2014 FZ71 in our numerical simulations. This distance is just below the 40 au upper limit Gomes et al. (2008, pp. 259–273) suggest for the KR and Neptune MMR objects. 2014 FZ71 is an interesting case that appears to be near the limits of effectiveness for the MMR+KR mechanism to operate. It is possible that 2014 FZ71 is a more extreme case of (145480) 2005 TB190, which Gomes et al. (2008, pp. 259–273) suggest was created by the Neptune 4:1 MMR+KR interactions.

3.2. A Large Population of MMR+KR 3:1 Resonance Objects

2015 FJ345, 2013 FQ28, and 2015 KH162 all have orbits near the 3:1 MMR with Neptune. In our numerical simulations, some of 2015 FJ345’s and 2013 FQ28’s one sigma clones showed oscillating resonant argument angles with Neptune’s 3:1 MMR. 2015 KH162 and its clones showed no oscillating resonant argument angles and is thus likely a fossilized 3:1

MMR+KR object. 2015 KH162 appears similar to (385607) 2005 EO297, which Gomes et al. (2008) suggest was created from MMR+KR interactions. 2013 FQ28 and especially 2015 FJ345 have much higher perihelia and less eccentric orbits, and thus have commonalities with 2004 XR190 and 2014 FZ71. 2015 FJ345 has the lowest eccentricity and highest perihelia of the 3:1 objects, which is consistent with the MMR+KR being responsible since 2015 FJ345 also has the highest inclination. The minimum perihelia for all these 3:1 objects could be below 35 au through the MMR+KR mechanism, allowing strong interactions with Neptune (Figure 4). Our new discoveries, 2015 FJ345 and 2013 FQ28, are the first two objects to have very high perihelia orbits through the 3:1 Neptune MMR+KR (both also have inclinations above 25°). As seen in Figure 2, there is also a cluster of objects near the 3:1 Neptune MMR with perihelia just below 40 au.

3.3. Other High-perihelion, Moderate Objects

There are a few objects in Figure 3 that have moderately high perihelia but are not near Neptune MMRs. The closest resonance for 2014 FC69 and 2013 JD64 is the 11:3. Both of these objects have very high inclinations of $30^\circ.1$ and $50^\circ.3$, respectively, strongly suggesting that their orbits were created through some interaction with the KR. 2014 QR441 is also not near any major Neptune MMR, although the moderately strong 10:3 resonance is nearby. 2014 QR441 has a very high inclination of $42^\circ.2$, again showing the KR is likely involved.

We also find that 2008 ST291 is likely a 6:1 resonance or fossilized resonance object that has probably been modified by the MMR+KR mechanism. Though the nominal orbital position does not, clones a few tenths of astronomical unit lower in semimajor axis show resonant argument librations (the

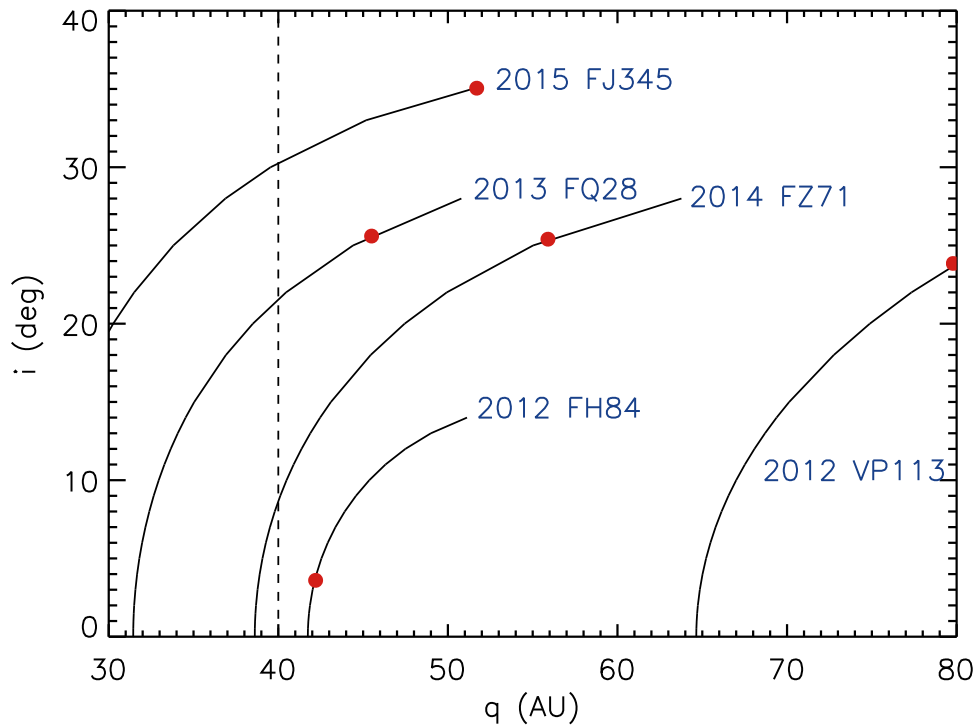


Figure 4. MMR+KR curves for some objects. An object that interacts with a Neptune MMR and the KR can have its inclination and perihelion (linked to eccentricity) altered through the relation $H = \sqrt{1 - e^2} \cos(i)$, where H is a constant and $q = a(1 - e)$. An object needs to come within about 40 au for the MMR+KR to be viable. This fails for the extreme or inner Oort cloud objects like 2012 VP113 or for the outer classical belt objects like 2012 FH84. 2014 FZ71 is near the limit for the MMR+KR mechanism. The MMR+KR mechanism can sufficiently explain 2015 FJ345's and 2013 FQ28's high-perihelion orbits.

e^5) for 2008 ST291's orbit in our numerical simulations, where $10^\circ < i < 35^\circ$, $0.40 < e < 0.65$ and $35 < q < 58$ au occurred over 1 Gyr. 2010 ER65 could be a similar 6:1 case, but we found no significant resonant argument librations.

3.4. The Outer Classical Belt

Our new discovery, 2012 FH84, also has a high perihelia and moderate semimajor axis and eccentricity (Table 1), but it has a very low inclination of only 3.6° and is between the 5:2 and 8:3 Neptune MMRs, which makes it less likely to have been created by MMR+KR. Its minimum perihelion would be about 42 au through this mechanism, so Neptune would be unlikely to have strong interactions. 2012 FH84 is similar to 1995 TL8 ($a = 52.3$ au, $e = 0.234$, $i = 0.2$ deg), which cannot be explained by the MMR+KR mechanism (Gomes et al. 2008). 2012 FH84 is thus likely a new member of the rare outer classical belt of objects. These are non-resonant objects that have semimajor axes just beyond the 2:1 resonance, with moderate to low eccentricities and low inclinations. This outer belt might be related to the low inclination objects in the main classical Kuiper Belt, as they have similar dynamics and very red colors (Gomes et al. 2008; Morbidelli et al. 2008; Sheppard 2010). 2002 CP154 and 2001 FL193 are the only other objects beyond 50 au that have perihelia higher than 40 au and low inclinations like 2012 FH84 and 1995 TL8 (Figure 3). 2014 FA72, 2013 GQ136 and 2003 UY291 are also near this region with low inclinations and perihelia above 40 au but have semimajor axes just below 50 au.

The new object, 2015 GP50, has a very similar semimajor axis and eccentricity to 2012 FH84, but 2015 GP50's significantly higher inclination could allow it to obtain a much lower perihelion. 2015 GP50 again is not obviously near a

Neptune MMR, but the strong 5:2 resonance is nearby. 2005 CG81's and 2007 LE38's similarly high perihelia and highly inclined orbits are also close to the 12:5 Neptune MMR.

4. DISCUSSION AND CONCLUSIONS

The moderate eccentricity space just beyond the Kuiper Belt edge at 50 au is shown to be populated with objects other than 2004 XR190. All the new moderate eccentricity, very high perihelion objects ($q > 45$ au) are near strong $N:1$ Neptune MMRs. We find all the moderate eccentricity objects with perihelia above 40 au and semimajor axes beyond 53 au have inclinations above 20° (except for the outer classical 2012 FH84 detailed above). Those away from Neptune $N:1$ MMRs generally have the highest inclinations, which presents evidence that the KR alone can raise the perihelion of high-inclination objects while more moderate inclinations require the addition of MMRs (Figure 3). We used our observational bias simulator detailed in Trujillo & Sheppard (2014) to examine the distribution of inclinations of the MMR+KR objects in Table 1. Using the $\sin i$ /single Gaussian functional form for inclinations in Gulbis et al. (2010), we find the debiased inclination distribution of the MMR+KR objects to be $\mu_1 = 28_{-1}^{+2}$ degrees and $\sigma_1 = 2.5_{-0.8}^{+2.2}$. This is significantly greater than the scattered objects with $\mu_1 = 19.1_{-3.6}^{+3.9}$ and $\sigma_1 = 6.9_{-2.7}^{+4.1}$ (Gulbis et al. 2010).

The few colors that have been obtained for these high-perihelion, moderate orbit objects show them to be typical of scattered disk objects (Sheppard 2010). If these two populations of objects were both originally from the same population, it suggests that the action of the MMR+KR is responsible for the larger inclinations seen in Table 1. These objects were likely scattered into these orbits and captured into resonances.

Whatever created the Kuiper Belt edge likely occurred during or before the emplacement of MMR+KR fossilized objects like 2004 XR190, as these fossilized objects would likely have been lost like any other objects beyond the edge. This would suggest the edge was created before Neptune finished migrating outwards and created the fossilized MMR+KR objects.

Our observational bias simulator was further used to get a crude estimate on the MMR+KR population. We used a uniform simulated orbit distribution with a minimum of 0.1 eccentricity and 40 au perihelion with an inclination distribution described above. We would only detect the objects when beyond 50 au and expect no longitudinal bias as our survey is fairly uniform. Because some MMRs are closer than others we would expect population ratio detections of 1.0/0.97/0.79/0.38/0.17/0.09 for MMRs 5:2/8:3/3:1/4:1/5:1/6:1 assuming equal populations. The odds of finding three 3:1 high-perihelion MMR objects and no 5:2 or 8:3 objects by chance is 2.5% if their populations are equal (though increases to 7% if 2015 GP50 is in the 5:2). This suggests the 3:1 may harbor many more MMR+KR objects than the 5:2 or 8:3 MMR, which is surprising as Volk et al. (2016) find a large 5:2 MMR population with lower perihelia and Brasil et al. (2014a) suggest the 3:1 and 5:2 should be the most populated with MMR+KR objects. However, the low order $N:1$ resonances like the 3:1 are the strongest for diffusing scattered objects via MMR+KR (Gallardo 2006a). We find that about 2400^{+1500}_{-1000} MMR+KR 3:1 and about 1600^{+2000}_{-1200} 4:1 objects larger than 100 km in diameter likely exist with perihelia greater than 40 au with the 5:2 and 8:3 populations significantly smaller.

Trujillo & Sheppard (2014) first noticed that the extreme trans-Neptunian objects exhibit a clustering in their orbital angles and predict that a super-Earth planet exists beyond a few hundred astronomical units to create this clustering. Recently, Batygin & Brown (2016) obtained a possible rudimentary orbit for this planet predicted by Trujillo & Sheppard (2014). In our numerical integrations (see the Appendix) we found this planet ($a = 700$ au, $e = 0.6$ and $i = 30$ degrees) has no significant impact on the current MMR+KR objects, including the most distant 2008 ST291. We note that all five of our new MMR+KR objects along with 2004 XR190 have longitudes of perihelion ($LP = \omega + \Omega$) between about 80° and 190° , which is about 180° from the longitude of perihelion for the ETNOs.

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APPENDIX

Our simple numerical simulations were performed to determine the basic orbital properties and behavior of the newly discovered objects. We used the MERCURY numerical integrator (Chambers 1999). In our basic simulations we used the four giant planets Jupiter, Saturn, Uranus, and Neptune and added the mass of the terrestrial planets to the Sun. An additional simulation was run with all the same conditions but adding in a 15 Earth mass planet on an eccentric $e = 0.6$ orbit at 700 au to see how it might effect the orbits of the MMR+KR objects. The time step used was 20 days and all integrations ran for over 1 billion years. Orbital elements used were heliocentric converted from the barycentric output from the orbit fitting program by Bernstein & Khushalani (2000). In our simulations of the nominal orbits and 10 clones within 1 sigma of each new object's orbit we found no significant semimajor axis variability over 1 billion years. For most nominal orbits and clones the e for all the new objects only varied by 0.01–0.02 and the i at most by about 3° over 1 billion years. But some 1 sigma clones did show large variations in e and i indicating significant interactions with Neptune's MMRs. 2014 FZ71 with a tenth of an astronomical unit larger semimajor axis than the nominal position showed variations of $8^\circ < i < 32^\circ$, $0.50 > e > 0.23$ inversely with i and $38 < q < 58$ au over 100 Myr timescales, indicating interactions with Neptune's 4:1 MMR. A tenth of an astronomical unit smaller clone of 2013 FQ28 near the 3:1 Neptune MMR had i vary from 20 to 30 degrees and e from 0.2 to 0.4 giving a perihelion from 38 to 50 au over 1 billion years. The 2008 ST291's clones of a few tenths of an astronomical units smaller than the nominal position showed significant orbital variability in e and i . 2008 ST291's clones in the Neptune 6:1 MMR resonance where the MMR+KR mechanism allowed i to vary from 35° to 10° and e inversely from 0.40 to 0.65 over 100 Myr (with perihelia ranging between 35 to 58 au). Including the distant massive planet did not cause the clones of 2008 ST291 to escape the 6:1 Neptune MMR or 2014 FZ71 to escape the 4:1 Neptune MMR and their basic orbital behavior was similar to the simulations without the putative distant massive planet.

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