THE CANADA–FRANCE ECLIPTIC PLANE SURVEY—L3 DATA RELEASE: THE ORBITAL STRUCTURE OF THE KUIPER BELT

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ABSTRACT

We report the orbital distribution of the trans-Neptunian comets discovered during the first discovery year of the Canada–France Ecliptic Plane Survey (CFEPS). CFEPS is a Kuiper Belt object survey based on observations acquired by the Very Wide component of the Canada–France–Hawaii Telescope Legacy Survey (LS-VW). The first year’s detections consist of 73 Kuiper Belt objects, 55 of which have now been tracked for three years or more, providing precise orbits. Although this sample size is small compared to the world-wide inventory, because we have an absolutely calibrated and extremely well-characterized survey (with known pointing history) we are able to de-bias our observed population and make unbiased statements about the intrinsic orbital distribution of the Kuiper Belt. By applying the (publically available) CFEPS Survey Simulator to models of the true orbital distribution and comparing the resulting simulated detections to the actual detections made by the survey, we are able to rule out several hypothesized Kuiper Belt object orbit distributions. We find that the main classical belt’s so-called ‘cold’ component is confined in semimajor axis (a) and eccentricity (e) compared to the more extended “hot” component; the cold component is confined to lower e and does not stretch all the way out to the 2:1 resonance but rather depletes quickly beyond a = 45 AU. For the cold main classical belt population we find a robust population estimate of \( N(H_g < 10) = 50 \pm 5 \times 10^3 \) and find that the hot component of the main classical belt represents \( \sim 60\% \) of the total population. The inner classical belt (sunward of the 3:2 mean-motion resonance) has a population of roughly 2000 trans-Neptunian objects with absolute magnitudes \( H_g < 10 \), and may not share the inclination distribution of the main classical belt. We also find that the plutino population lacks a cold low-inclination component, and so, the population is somewhat larger than recent estimates; our analysis shows a plutino population of \( N(H_g < 10) \sim 25_{-15}^{+25} \times 10^3 \) compared to our estimate of the size of main classical Kuiper Belt population of \( N(H_g < 10) \sim (126_{-56}^{+50}) \times 10^3 \).

Key words: Kuiper Belt – surveys

Online-only material: color figures

1. INTRODUCTION

In 1949 Edgeworth, and in 1951 Kuiper, postulated the existence of a debris disk beyond the orbit of Neptune. Their expectation was based on the hypothesis that material in this zone had likely not formed into large planets (Irwin et al. 1995). Pluto had been discovered two decades earlier but was not recognized at the time as a large member of this hypothesized disk of debris. Several decades would pass before a few researchers began to search in earnest for small bodies beyond Neptune. These searches were motivated by the realization that the discovery and study of the orbits and properties of the members of such a debris disk could provide a rich understanding of the formation and evolution of the outer solar system. For example, the objects may be composed of some of the most pristine materials left over from the formation of the solar system. Also, a measure of the mass and orbital distribution of objects in this zone of the solar system could confirm this region as the source of short period comets.

The discovery of the first object recognized to be a member of the outer solar system debris disk, 1992 QB1 (Jewitt et al. 1992), led to an avalanche of searches and discoveries. In a mere 15 years, observers have discovered over 1200 small trans-Neptunian bodies. A gold rush of discovery compared with the case of asteroids, where over 130 years were needed to discover a comparable number; only four asteroids were known for over 44 years after the discovery of the first, Ceres. Some of these outer solar system bodies are estimated to be larger than Pluto, which itself is now understood to be one of the largest and closest of the Kuiper Belt objects (KBOs).
1.1. Initial Impression of the KBO Orbit Distribution; Influence on Survey Progress

Jewitt et al. (1996) provided one of the first estimates of the size and shape of the Kuiper Belt. In this early work they considered the biases against detections of high-inclination objects and determined that the intrinsic width of the Kuiper Belt is likely around ∼30° FWHM, much broader than anticipated. As surveys of the Kuiper Belt have continued, observers are becoming more aware that a correct assessment of all observational bias is critical if one is to correctly measure the intrinsic distribution of material in the distant solar system. Over the past decade, a number of surveys (Jewitt et al. 1998; Larsen et al. 2001; Trujillo et al. 2001; Gladman et al. 2001; Allen et al. 2002; Jones et al. 2006) have further refined these statistics and Elliot et al. (2005) provide the survey of the Kuiper Belt with the largest number of detected and tracked objects. A compilation of the detection rates and subpopulation estimates from these KBO surveys can be found in the Kavelaars et al. (2008). These previous surveys have provided exciting insights into this region of the solar system.

The precise determination of a KBO orbit often requires an observational arc of many years in length. The long time commitment and frequent observations often lead to observational biases that are difficult to account for (see Jones et al. 2006; Kavelaars et al. 2008, for further details). A survey which desired to provide a detailed and accurate description of the underlying Kuiper Belt population must pay very close attention to survey characterization. In the Canada-France-Ecliptic Plane Survey (CFEPS) we have taken great pains to characterize and track the survey detections so that one can make robust statements regarding the underlying orbital distribution in the Kuiper Belt. In the CFEPS project we have tracked ∼85% of our characterized detections (see Section 3.1), to-date this is the highest fraction of tracked objects for any KBO survey. Though the sample we report here is only ∼5% of the world inventory of KBOs with known orbits, we are able to make a number of interesting and new statements regarding the intrinsic orbital structure of the Kuiper Belt region because of our careful attention to the survey characteristics.

In Sections 2 and 3, we describe the observations and characterization of the CFEPS L3 KBO sample. In Section 4, we explain the use of our survey simulator and statistical methods and in Section 5 we describe our parametrized models of the KBO orbit distribution and provide estimates of the total number of objects in each subpopulation modeled.

2. OBSERVATIONS

The CFEPS project uses images acquired by the Very Wide component of the Canada-France-Hawaii Telescope Legacy Survey (LS-VW) for discovery and a large fraction of the follow-up imaging. LS-VW observations where made using the one degree field of view of the CFHT MegaPrime camera. CFHT MegaPrime provides well sampled images with a typical image quality of 0.7–0.9 arcsec FWHM. The LS-VW observations were designed to maximize the opportunity to discover and track trans-Neptunian objects (TNOs) while providing multi-filter, multi-epoch imaging that could be used to pursue secondary science goals. The LS-VW project was awarded 50 nights per year on CFHT to allow observations to cover a sky area of about 1300 square degrees along the ecliptic (the entire sky within 2 degrees of the ecliptic plane and more than 10 degrees from the galactic plane). The survey started in 2003 March and was severely hampered by technical and weather problems for the first 3 semesters of operation. In 2005 May the Scientific Advisory Committee of the CFHT, reacting to a lower than anticipated observing efficiency of the CFHT Legacy Survey, ramped down the LS-VW observations such that only 400 of the originally anticipated 1300 square degrees were covered.

This manuscript details the observational campaign and analysis arising from those KBOs detected in the first calendar year of the LS-VW project. These KBOs (discovered in ∼94 square degrees of imaging in 2003) are referred to as the L3 data release because our internal designation of these detections all begin with the string “L3”.

Many of the KBOs recorded in the Minor Planet Center (MPC) database lack precise orbital elements and all contain biases, some of which are hidden. These biases often result in misinterpretation of the orbital distributions recorded in the MPC lists. The CFEPS observing strategy was developed with the goal of providing a set of high-quality KBO orbits free of tracking/ephemeris bias. Our discovery and followup program, coupled to “data releases” that provide only high-quality orbits, is specifically designed to reduce the biases present in the main MPC listing. LS-VW observations were made on at least six separate nights, with about fifteen separate observations of each field over the course of 3–4 years. A summary of our observing sequence is given below, a complete description of our observing strategy and logic is presented in Jones et al. (2006).

- **Discovery:** a set of 3 observations, separated by approximately 1 hr, targeting fields within 15° of opposition to allow detection of solar system objects via their reflex sky motion.
- **Nailing:** a single observation a few nights before or after the discovery tripod. These observations provided confirmation of the discovery observations.
- **Checkout:** a second set of three exposures. These observations are made when the field is at solar elongation between 125 and 110 degrees to avoid confusion with main-belt asteroids (see Figure 1). These observations provide the required sky motion arc so that ephemeris predictions a year later have uncertainty of less than one-degree of arc and reducing the chances of introducing ephemeris biases into our catalog.
- **Recovery:** a tripod of observations made when the field returns to opposition, coupled with a second Nailing observation. These observations provide an enormous improvement to the ephemeris of outer solar system objects and secure their positions for continued monitoring.
- **Refinement:** a final tripod of observations taken two years after discovery, providing orbital refinement to ≤ 0.1% relative accuracy. For some objects additional observations were acquired three or even four years after discovery to provide needed improvements in the astrometry when fine orbital details are desired (to determine resonant libration, for example).

The LS-VW CFHT MegaPrime observations imaged a grid of pointings using the g′, r′, and i′ filters (Magnier & Cuillandre 2004). Fields, *not KBO ephemerides*, were targeted in the pre-refinement stages of this survey. The observing strategy ensures that our tracking observations are free of “ephemeris biases”: orbit distribution biases induced by assuming orbits of the KBOs discovered in each field (see Kavelaars et al. 2008; Parker et al. 2007). Using a pointing-grid and ensuring that each field was observed in each filter enhanced the legacy value of the
Figure 1. Angular rates of motion for objects on circular ecliptic-plane orbits with semimajor axis near the asteroid belt (dash lines show rates for objects at 2 and 6 AU) and the Kuiper Belt (dotted lines show rates of motion of objects at 30 and 100 AU). At solar elongation of ∼ 140° KBOs and main belt asteroids have similar angular rates of motion (gray area of plot), observing at elongation between 125° and 155° results in confusion between asteroids and KBOs in recovery observations.

Table 1
Summary of Field Positions and Detections

| Block | R.A. (hrs) | Decl. (deg) | Fill Factor | Disc. Tracked | Geometry DEG DEG | Limit gAB |
|-------|------------|-------------|-------------|---------------|-----------------|----------|
| L3f   | 12:42      | −04:33      | 0.89        | 4  3          | 4 x 4           | 23.75    |
| L3h   | 13:03      | −06:48      | 0.81        | 20 12         | 4 x 4           | 24.45    |
| L3q   | 22:01      | −12:04      | 0.89        | 9  7          | 4 x 4           | 24.08    |
| L3s   | 19:43      | −01:20      | 0.87        | 6  6          | 14 x 1          | 23.95    |
| L3w   | 04:33      | 22:21       | 0.87        | 19 14         | 16 x 1          | 24.25    |
| L3y   | 07:30      | 21:48       | 0.85        | 15 13         | 4 x 4           | 24.08    |
| Total |            |             |             | 73 55         | 94 sqr. deg.    |          |

Notes. Field centers. R.A./Decl. is the approximate center of the field. Fill Factor is the fraction of sky covered by the mosaic and useful for KBO searching. gAB refers to the g-band AB scale of the SDSS photometric system.

Tables 1 and 2 provide a summary of the area, field geometry, filter coverage, exposure time, image quality and flux limits of the LS-VW observations and Figure 2 presents the geometry of a typical LS-VW observing block. Flux limits were determined by added artificial sources, with a range of fluxes and reflex motions, into the original images and determining the fraction of artificial sources detected by our detection pipeline (see Jones et al. 2006, for details).

We experimented with conducting the discovery observations in the g’ and r’ filters, eventually standardizing on conducting all discovery observations in g’. Table 2 provides a detailed accounting of the relevant observational parameters of each block. The observational data acquired as part of the LS-VW are publicly available from the Canadian Astronomical Data Center.\footnote{http://www.cadc.hia.nrc.gc.ca}

Exposure times were chosen to ensure a limiting magnitude (see Table 2) of $m_{g'} \sim 24$, resulting in about one KBO detection per one square-degree FOV of the CFHT MegaPrime camera. This depth ensured that the discovered objects would be bright enough to permit tracking observations from telescopes with apertures as small as two meters diameter while maintaining a reasonable duty cycle per discovery field. To achieve this depth we elected to acquire 70 s exposures through the CFHT MegaPrime g’ filter; sufficient to provide S/N ∼ 8 on $m_{g'} \sim 24.1$ point sources in median (FWHM ∼ 0’8) CFHT seeing ($\langle (m_{g'} - m_R)_{KBO} \rangle \sim 0.8$).

Object motion was detected by re-observing each field three times with a minimum time separation of 30 minutes between exposures. To ease implementation within the CFHT queue system we programmed our observations in sequences such that the exposure length plus overhead between iterations provided the required temporal sampling. Given the expected overhead of 40 s per exposure and the 70 s exposure time, and the desire for at least 30 minutes between repeated exposures requires approximately 16 fields to be observed per cycle. We refer to each of these groups of ∼16 fields as an observation “block.”

Checkup observations were used to eliminate confusion in orbit linkages between discovery and recovery. These off-opposition observations also greatly reduce orbital uncertainties in a multi-opposition orbit. Checkup observations target the same pointing grid as the discovery observations, occurring...
either in the months before (pre-checkup) or following (checkup) the block’s passage through opposition. The ephemeris uncertainty for KBOs with only a one day arc (based on our discovery and nailing observations a few months before or after checkup) can be quite large (see Jones et al. 2006); to avoid confusion with main-belt asteroids, we ensured that all check-up fields were observed between solar elongation of 110 and 125 degrees (see Figure 1). Given this narrow range of elongation and our desire to keep all the fields observable over a minimum of 5 nights per dark run, we were restricted to field geometries that occupied no more than ~ 15° of RA. Simultaneously, we maximized the R.A. size of each patch, in order to minimize the number of objects that sheared out of the field of view between discovery and checkup. Four of the L3 patches are roughly square R.A./decl. patches, (see Figure 2 for example) while two were observed as long strips. The geometry and central R.A./decl. of each of the six L3 blocks is given in Table 1.

2.1. Longitude Coverage

Observations where acquired as part of a queue-scheduled survey at the CFHT. Our fields were chosen to lie within 2 degrees of the ecliptic plane and the CFHT QSO (queue service observer) imaged those fields that were at opposition whenever our priority on the facility was higher than that of competing programs. This “pressure” balancing approach to the initial discovery observations resulted in about one “block” of observations per CFHT queue observing session (nominally the 7 days leading and trailing the new moon). As a result, the CFEPS sky coverage will span nearly the entire R.A. range with breaks near the galactic plane crossings (where we did not request observations) and at locations of very high queue pressure (typically May and October). The sky coverage of our L3 release is 94 square degrees (see Table 1).

3. SAMPLE CHARACTERIZATION

Each of the discovery blocks listed in Table 1 was searched for KBOs using our Moving Object Pipeline (MOP; see Petit et al. 2004). The detection flux limit (above which 40% of all artificial sources where recovered by the MOP) for each field is listed in Table 2, along with information about the filter sequencing.

TNOs detected in each of the discovery images are given a provisional CFEPS designation of lower-case letter “l” followed by the number 3 (indicating detection in 2003) followed by the letter of the block in which the detection occurred (each block is given a letter corresponding to the two-week period during which the discovery observations were made, similar to the MPC provisional designation system) finally an odometer number is added which counts up the number of KBOs detected in the block.

The provisional lower-case “l” is switched to an “L” once an object has been tracked to the “Checkup” phase, such objects are more likely to be recoverable in the second opposition (Parker et al. 2007). The 73 KBOs that received an “I” (14) or “L” (59) designation constitute our discovery sample. Other KBOs, such as 2004 XR190 (a.k.a. Buffy, Allen et al. 2006), discovered during tracking observations, are not included in our modeling samples and are reported to the MPC. Only those KBOs discovered in those images that we designate as our “discovery” images are considered as part of our survey sample. We then searched the MPC for objects at the same R.A./decl. location and any object which could be linked with a previously detected KBO was given the suffix designation PD. For example, the object L3q02PD was detected in the Legacy Survey data taken in the 17th two-week interval of 2003, and is a previously known KBO (2001 QB298).

3.1. Photometry and Detection Efficiency

The LS-VW observations are acquired as part of the CFHT queue system. For each field observed on a photometric night the CFHT QSO provides calibrated images using their ELIXIR processing software (Magnier & Cuillandre 2004). Our photometry is reported in the AB zero-point system defined by ELIXIR combined with an average color term for the camera run of the observation. All of the CFEPS discovery observations were acquired in photometric conditions. Using differential aperture photometry we measure the total flux for each of our detected objects on all photometric nights and these fluxes are reported in Table 3.

The photometric calibration of the discovery triplets to a common reference frame and determination of our detection efficiency is required for our survey simulator analysis. To characterize our detection efficiency we inserted artificial sources, moving on the sky with rates typical of KBOs, into our CCD images and then determine our efficiency of recovering these artificial sources by running the images through MOP, the same detection pipeline as used in discovery processing. Most of our discovery observations were made using the $g'$ filter at CFHT, with some made using the $r'$ filter. For fields observed in $r'$ we shifted the limits to a nominal $g'$ value using a color of $(g' - r') = 0.73$, typical of the $(g' - r')$ in our sample (see Table 3). Our
detection and characterization processes are fully described in Petit et al. (2004) and Jones et al. (2006).

Those objects in each block that have a magnitude above the block’s 40% detection probability are considered to be part of the L3 characterized sample. Our pipeline detection has a human-operator confirmation step for real objects; the detection efficiency, however, is determined later by implanting hundreds of artificial objects per CCD and these sources are found without the operator confirmation step. Determining the detection efficiency of the artificial objects using a human-operator was too time consuming for the ~10^5 artificial objects used to characterize the detection efficiency of the L3 fields. Below ~40% the detection efficiencies determined by human operators and MOP diverge (Petit et al. 2004); since characterization is critical to the CFEPS goals, we are unable to utilize the sample faintward of the measured 40% detection efficiency level. The characterized L3 sample is those 57 objects (of the 73 discovered) whose flux at detection is above the 40% detection threshold for their block; this represents roughly 80% of the discovery sample, consistent with the shape of the KBO luminosity function and typical decays in detection efficiency. These 57 KBOs make up our characterized sample (see Table 3 for a list of KBOs considered part of this sample).

Our discovery and tracking observations were made using short exposures designed to maximize the efficiency of detection and tracking of the KBOs in the field. These observations do not provide the high-precision flux measurements necessary for possible classification using broadband-colors of KBOs and we do not comment on this aspect of the L3 CFEPS sample.

### 3.2. Tracking and Lost Objects

Tracking during the first opposition was done using the built-in follow up of the LS-VW project. Subsequent tracking, over the next three oppositions, occurred at a variety of facilities, including CFHT. The observational efforts are summarized in Table 4. In spring 2006 the CFEPS project made an initial data release of the complete observing record for the L3 objects (before all the refinement observations for all objects were complete). The L3 release was reported to the MPC (Gladman et al. 2006; Kavelaars et al. 2006a, 2006b) and additional followup that has occurred since the 2006 release has also been reported to the MPC. Detailed data for the L3 objects can be found on the CFEPS web site at [http://www.cfeeps.net](http://www.cfeeps.net) where updated electronic tables of all of the information in this paper can be obtained. The correspondence between CFEPS internal designations and MPC designation can be determined using...
Tables 5 and 6. The tracking observations provide sufficient information to allow reliable orbits to be determined such that ephemeris errors are smaller than a few tens of arc-seconds over the next five years. Of the 73 (57) KBOs in our L3 discovery (characterized) sample 55 (48) have been tracked through 3 oppositions or more (i.e., not lost) and their orbits are now known to a precision of $\Delta a/a < 0.1\%$ and can be reliably classified into orbital subpopulations (see below). The very high tracking fraction (fraction of characterized sample objects tracked) for the CFEPS project (84% of KBOs in our L3 characterized sample have been tracked to 3 or more oppositions) is a testament to careful planning of our survey strategy. The initial tracking of KBOs discovered by CFEPS is through blind return to the discovery fields to ensure that there is no orbital dependency in the tracked fraction. We do find, however, that the tracked fraction is a function of the magnitude of the KBO and have characterized this bias. For the L3 fields we find

$$f_t(m_g) = \begin{cases} 
1.0 & (m_g < 22.8) \\
1.0 - 0.25(m_g - 22.8) & (m_g > 22.8) 
\end{cases}$$

Notes. $p$ indicates that the orbit classification is provisional. $MPC_w$ indicates object was in MPC database but found $+1^\circ$ from predicted location.

Object flux below 40% detection efficiency level; object not used in modeling.

Object flux below 40% efficiency level in discovery observation and not used.

Notes. UT Date is the start of the observing run; No. Obs. is the number of astrometric measurements reported from the observing run.

Table 4

Follow-up/Tracking Observations

| UT Date       | Telescope | No. Obs. |
|---------------|-----------|----------|
| 2002 Aug 4    | CFHT      | 6        |
| 2002 Sep 3    | NOT 2.56 m| 6        |
| 2002 Sep 4    | CFHT 3.5 m| 9        |
| 2002 Sep 29   | CFHT 3.5 m| 6        |
| 2002 Nov 27   | CFHT 3.5 m| 10       |
| 2004 Feb 18   | WIYN 3.5 m| 4        |
| 2004 Apr 14   | Hale 5 m reflector| 73   |
| 2004 May 23   | Mayall 3.8 m| 6        |
| 2004 Sep 5    | KPNO 2 m | 15       |
| 2004 Sep 10   | Mayall 3.8 m| 25       |
| 2004 Sep 15   | Hale 5 m | 20       |
| 2005 Jul 8    | Gemini 8 m| 28       |
| 2005 Jul 8    | Hale 5 m | 20       |
| 2005 Jul 10   | ESO 2.2 m| 4        |
| 2005 Aug 1    | VLT UT-1 | 15       |
| 2005 Oct 2    | Hale 5 m | 33       |
| 2005 Nov 3    | Mayall 3.8 m| 23       |
| 2005 Dec 3    | MDM 2.4 m| 10       |
| 2006 Jan 27   | Hale 5 m | 35       |
| 2006 Nov 22   | WIYN 3.5 m| 4        |

Notes. UT Date is the start of the observing run; No. Obs. is the number of astrometric measurements reported from the observing run.

Table 5

Resonant Objects

| Designations | $a$ (AU) | $e$ | $i$ (°) | Dist Res | Amp. | Comment |
|--------------|---------|----|--------|----------|------|---------|
| L3y11        | 131697 | 34.925 0.0736 | 2.856 34.0 5.4 | 75 ± 5 | MPC | L3y06 |
| L3s06        | 2003 SS317 0.2360 | 5.905 28.2 4.3 | 60 ± 20 |
| L3s02        | 2003 SO317 0.2750 | 6.563 32.3 3.2 | 100 ± 20 |
| L3b11        | 2003 HA57 0.1710 | 27.626 32.7 3.2 | 70 ± 5 |
| L3b19        | 2003 HF57 0.194 | 1.423 32.4 3.2 | 60 ± 20 |
| L3w07        | 2003 TH58 0.0911 | 27.935 35.8 3.2 | 100 ± 10 |
| L3w01        | 2005 TV189 0.1884 | 34.390 32.0 3.2 | 60 ± 20 |
| L3h14        | 2003 HD57 0.179 | 5.621 34.9 3.2 | 60 ± 30 |
| L3s05        | 2003 SR317 0.1667 | 3.848 35.5 3.2 | 90 ± 5 |
| L3h01        | 2004 FW164 0.1575 | 9.114 33.3 3.2 | 80 ± 20 |
| L3y06        | 2003 YW179 0.1537 | 2.384 55.7 5.3 | 100 ± 20 |
| L3y12PD      | 126154 | 42.332 1.0403 | 11.078 36.4 5.3 | 100 ± 10 |
| L3q08PD      | 135742 | 43.63 0.125 | 5.450 40.7 7.4 | 100 ± 10 |
| L3w03        | 2003 YJ179 0.0794 | 1.446 40.3 7.4 | 30 ± 40 |
| L3s04*       | K03SV7P | 45.961 0.1694 | 5.080 44.9 17.9 | 40 ± 40 |
| L3y07        | 131696 | 52.92 0.3221 | 0.518 36.6 7.3 | 100 ± 20 | MPC |
| L3q04PD      | 60621 | 55.29 0.4020 | 5.869 36.0 5.2 | 80 ± 30 |
| L3y02        | 2003 YQ179 0.388 0.5785 | 20.873 39.3 5.1 | ... | p |

Table 6

Nonresonant Objects

| Designations | $a$ (AU) | $e$ | $i$ (°) | Dist Res | Amp. | Comment |
|--------------|---------|----|--------|----------|------|---------|
| L3w06        | 2003 YL179 | 38.82 | 0.002 | 2.525 | 38.7 |
| L3y14PD      | 131695 | 37.219 0.05211 | 4.262 35.3 | p 11.8 |

Notes. $p$ orbit classification is provisional; object may be in the M:N resonance.

$a$ Object flux below 40% efficiency level in discovery observation and not used in modeling.

$a$ Flux below 40% detection efficiency level; object not used in modeling.
Our pre-survey discovery observations were made in the “R” band and we have transformed our pre-survey limits to $g_{AB}$, for use in our survey simulator, using a constant color offset of $(g_{AB} - R) = 0.8$ (Hainaut & Delsanti 2002).

### 3.3. Orbit Classification

Kuiper Belt objects are subdivided into broad dynamical classes based on their orbital elements and dynamical behavior. Using the procedure fully described in Gladman et al. (2008) (similar to that described in Chiang et al. 2003), we report the L3 sample classifications as of March 2008 (including all refinement observations to date). Briefly, based on all available astrometry we determine the distribution of elements consistent with the observation for each object. A best fit and two extremal “clones” consistent with the observations are integrated for $10^7$ years and their orbital evolution is used to provide the classification. If the three orbital evolutions provide the same answer, the classification is deemed to be “secure”; if not the classification is insecure and further refinement observations are needed. The results of this exercise are given in Tables 5 and 6. Based on current knowledge of the L3 sample seven objects remain insecure (even though these have 5 opposition observational arcs!), and all of these are due to their proximity to a resonance border where the remaining astrometric uncertainty makes it unclear if the object is actually resonant. For these “insecure” objects we list them in the category shown by two of the three clones and note the other possible classification (see Table 5 and 6).

We find that 33 (60%) of our L3 tracked sample are in the classical belt, 18 (33%) objects are in a mean-motion resonance with Neptune, 8 (15%) of which are plutinos, the remaining sample consists of 2 (4%) objects on scattering orbits and 2 (4%) in the detached population. Given these orbital classification in our observed population we now determine a process for the parametrization the intrinsic population of the Kuiper Belt implied by our observations; the wildly different detectability of these populations in a flux-limited survey implies that the “true” population ratios may be different from the observed ones.

### 4. THE SURVEY SIMULATOR

The KBO sample detected in a survey of outer solar system bodies is a biased representation of the underlying population (see Kavelaars et al. 2008 for a more detailed discussion). The CFEPS project is designed to minimize biases inherent in how a survey is conducted; we are, however, still subject to the strong selection effects imposed by our pointing distribution and substantial flux biases. We proceed by examining both the orbital distribution of the L3+Pre sample as well as the distribution of orbital elements as reported by the MPC. By examining the observed orbit distributions of each of the Kuiper Belt subpopulations we can then make some initial guesses as to likely parametrization of the intrinsic population. Then, through extensive use of the survey simulator, we pare away those intrinsic models that are inconsistent with our characterized sample. Regardless of how well we might reproduce the observations, one should remember that the parametrization used here is completely ad hoc, and should not be viewed as resulting from any specific model of the formation and evolution of the KBO population.

Although we make some progress here, a reliable description of the internal orbital structure (of say the insides of the 3:2 resonance) will require factors of many to orders of magnitude larger sample sizes than we have available from our calibrated L3+Pre survey catalog. We anticipate that the complete CFEPS sample (L3, L4, and L5), which will contain roughly 200 well-characterized orbits, will be available before the end of 2009.

### 4.1. Parametric Models

Our goal is to determine the intrinsic population of KBOs that is consistent with our observations. A standard approach would be to use these observations to constrain some reasonably agreed upon parametrized model of the orbital distribution of KBOs. There is, unfortunately, no such model; the Kuiper Belt has arrived in the current state by a complex sequence of events related to planetesimal accretion, gravitational erosion, possibly planet migration, possibly resonance sweeping, and perhaps sculpting by large rogue objects. The only models we have today to describe the KBO population are the results of long term numerical integration, with limited resolution of all but the most numerous dynamical subpopulations, and no possibility to vary parameters to fit the observations. To circumvent this limitation here, we rely on ad-hoc parametrization of the various dynamical subpopulations. Our hope is that these parametrization will guide future dynamical modeling.

We proceed by examining both the orbital distribution of the L3+Pre sample as well as the distribution of orbital elements as reported by the MPC. By examining the observed orbit distributions of each of the Kuiper Belt subpopulations we can then make some initial guesses as to likely parametrization of the intrinsic population. Then, through extensive use of the survey simulator, we pare away those intrinsic models that are inconsistent with our characterized sample. Regardless of how well we might reproduce the observations, one should remember that the parametrization used here is completely ad hoc, and should not be viewed as resulting from any specific model of the formation and evolution of the KBO population.
4.2. Statistical Tests

Once we have decided on a model, given either by a set of parametrized distributions, or as the result of a full-fledged numerical simulation of the formation and evolution of the outer solar system, we pass the model orbit catalog into our survey simulator and obtain a set of simulated detections. These detections represent those KBOs our survey would detect if the input model is a reasonable representation of the intrinsic KBO population. Given these simulated detections, we compare their orbital-element distribution with those of the real objects.

Ideally we would compare the multidimensional distribution of all orbital elements simultaneously; given the small sample sizes being considered, a multidimensional approach is not warranted. Instead we rely on a series of one-dimensional distribution tests, using either the Anderson–Darling (AD) statistic (for elements \(a, e, i, q, \Delta\)) or the Kuiper-modified Kolmogorov–Smirnov (KKS) D-statistic for cyclic variables (elements \(M, N, \omega\)). The AD test statistic is chosen since this statistic is more responsive to the tails of a distribution than the more traditional Kolmogorov–Smirnov test statistic.

Using the survey simulator we generate many thousands of simulated detections for a given intrinsic model and use these large simulated populations to bootstrap the relevant AD and KKS statistics. We then proceed as usual for these tests by rejecting models at a given confidence level of X% when the probability of finding an AD or KKS statistic value larger than the one computed when the model cannot be rejected, we reject a model based on its distribution (which a survey is most sensitive to via the observed element distributions) is not acceptable. The use of coupled orbit element distributions raises the specter of “double testing” — sometimes we reject based on \(a\) or \(e\) and other times on the basis of \(r\) or \(q\) and these are, in fact, measuring the same quantities with different couplings to the survey circumstance. However, we use \(a\) and \(e\) rejections to specifically tune the limits of our \(a\) and \(e\) distributions, and when examining the global acceptability of the model we then revert to the \(q\) and \(r\) distributions. In this way we avoid “double testing.”

4.3. Total Populations Estimates

Once a set of model orbital element distributions have been determined, essentially creating the parametrized Kuiper Belt, we can use these distribution functions to determine the total absolute population of the Kuiper Belt, subject to our model. We report our determination of the number of objects with absolute magnitudes \(H_p < 10.0\) for each subpopulation. The CFEPS survey did not detect any objects with \(H_p > 10\) and thus this value represents the global limit on our size sensitivity.

For each dynamical subpopulation, we draw objects from our model population until the survey simulator detects the same number of objects as in the real L3+Pre sample for that dynamical class. We repeat this process 2000 times and for each of these realizations we count the number of objects in the simulated population needed to account for the number of objects in the L3+Pre sample (see Figure 3).

We prefer to quote \(N(H_p < 10.0)\) as this number is independent of albedo. To convert our estimates to the number of KBOs larger than 100 km diameter one must assume an albedo and determined the measured luminosity for the Sun in a particular waveband. We denoted this albedo/luminosity dependent population estimate as \(N(D_p > 100 \text{ km})\). For objects that are visible only via reflected sunlight,

\[
H_p = m_{\odot}(x) + 42.38 - 2.5 \log_{10}(\rho_s D_p^2) \tag{1}
\]

where \(\rho_s\) is the \(x\)-band albedo of the TNO and \(m_{\odot}(x)\) is the Sun’s \(x\)-band magnitude. For the \(g^\prime\) filter, \(m_{\odot}(g^\prime) = -26.47\) (Willmer 2008). Scaling off a reference albedo of 0.05 and a reference diameter of 100 km yields:

\[
H_g = 9.16 - 2.5 \log_{10} \left( \frac{\rho_s}{0.05} \left( \frac{D_p}{100 \text{ km}} \right)^2 \right) \tag{2}
\]

The CFEPS observations are only sensitive to the brightest members of the KBO population and the luminosity function of this population is well represented by a uniform power-law size distribution (Petit et al. 2006). Starting from our \(N(H_g < 10)\) estimates (which corresponds to \(D_p \approx 70\) km for \(\rho_s = 0.05\)), the shift to a larger diameter is performed by a multiplication by \(10^{\alpha \times \Delta H}\) where \(\Delta H = 10 - H(D_p = 100 \text{ km})\) is the difference between \(H = 10\) and the magnitude corresponding to a diameter \(D_p = 100\) km. We adopt \(\alpha = 0.72\) for the slope of the magnitude distribution for all our modeling (Petit et al. 2006), leading to \(N(D_p > 100 \text{ km}) = 0.25 \times N(H_g < 10)\). Many previous
estimates of \(N(D_p > 100 \text{ km})\) were made assuming \(p \sim 0.04\), in which case \(N(D_p > 100 \text{ km}) = 0.37 \times N(H_q < 10.0)\). The magnitude of the corrections due to: albedo-dependent color (small), the slope of the magnitude distribution (moderate), and absolute albedo (large) render such comparisons difficult. Using \(N(H_q < 10)\) escapes from the albedo uncertainties and is only weakly dependent on our assumed value of \(\alpha\).

5. THE INTRINSIC ORBITAL DISTRIBUTION OF THE KUIPER BELT

We adopt the convention (Gladman et al. 2008) that the Kuiper Belt can be divided into four broad orbital classes: (1) resonant (objects currently in a mean-motion resonance with Neptune), (2) scattering (objects that experience close encounters with Neptune), and (3) classical belt (everything that is left). Following Gladman et al. we further subdivide the classical belt into (a) inner classical belt (objects with semimajor axis interior to the 3:2 resonance), (b) main classical belt (objects whose semimajor axis is between the 3:2 and 2:1 mean-motion resonances), (c) outer classical belt (objects with semimajor axis exterior to the 2:1 resonance with \(e < 0.24\)), and (d) detached (those objects with semimajor axis beyond the 2:1 resonance that have \(e > 0.24\)).

In the following sections we present the results of our search for an empirical parametrized orbit distribution for the main classical belt (33 members in the L3+Pre sample), as well that of the plutinos (eight members) and inner classical belt (two members). In each case we start with the a simplistic, yet plausible, parameterization of the intrinsic orbit distribution, compare that distribution to the L3+Pre sample, and then increase the complexity of the parameterization until arriving at a model that provides a statistically acceptable match to our sample. In this way we arrive at acceptable parametrizations of the main classical belt, the plutinos and the inner classical belt. Although these models are acceptable, we do not assert any statement regarding their uniqueness.

5.1. The Main Classical Belt

The main classical Kuiper Belt is well described as a population with a two component inclination distribution (see Levison & Stern 2001; Brown 2001; Elliot et al. 2005) and these two components also appear to have distinct surface properties (Tegler & Romanishin 1998, 2000; Trujillo & Brown 2002). The classical belt population also appears to have a limited radial extent, initially Dones (1997) noted that, even with the small handful of objects then known, either the luminosity function of Kuiper Belt objects is quite steep or the population does not extend beyond \(a \sim 50 \text{ AU}\). Jewitt et al. (1998) found that a classical Kuiper Belt with a flat radial distribution beyond 50 AU was inconsistent with their observations while Gladman et al. (2001) concluded that the observed radial distribution of KBOs in their survey was consistent with a radii distribution that declines beyond 50 AU. Further observations by Allen et al. (2001) demonstrated a lack of objects on circular orbits beyond 50 AU, and if the classical belt does extended beyond this distance then the surface density must drop dramatically. Additional strong evidence for an outer-edge to the classical Kuiper Belt came from Trujillo et al. (2001) and Trujillo & Brown (2001) and the more recent analysis of Hahn & Malhotra (2005) indicates that the lack of objects on circular orbits with \(a > 50 \text{ AU}\) is consistent with a classical Kuiper Belt that is truncated at \(a \sim 45 \text{ AU}\).

Jones et al. (2006) demonstrated that a filled phase-space model of the main classical belt, one that filled the available phase space down to a minimum perihelion of \(q_{\text{mm}} = 38 \text{ AU}\), was not rejected by their small, but well-characterized, sample. We passed this same model through the survey simulator, configured for the L3+Pre sample. We now reject this model at more than 99.9% confidence, dotted line in panel A of Figure 4. We now reject this model at more than 99.9% confidence, dotted line in panel A of Figure 4. (Figure 4 presents the \(a, e, i\) CDFs of the main classical belt model distributions as observed through our survey simulator.) The orbital information available within the CFEPS project has now reached the quality level where more precise modeling of the internal structure of the main classical belt can be tested.

5.1.1. An Initial Inclination Distribution

Recognizing that the observed inclination distribution of classical Kuiper Belt objects follows the shape of a two component Gaussian, Brown suggested an intrinsic model distribution of

\[
f_2(i) = \sin i \left( am \exp \left( \frac{-i^2}{2\sigma_c^2} \right) + (1 - am) \exp \left( \frac{-i^2}{2\sigma_h^2} \right) \right)
\]

where \(\sigma_c\) is the width of the “cold-component,” \(\sigma_h\) is that of \(^{13}\) Jones et al. (2006) did not provide an inclination distribution for their simple model, here we adopt an Gaussian inclination distribution with a width \(^{15}\).
the “hot-component,” and $a_{wp}$ is a weighting factor, not the fraction of the population that is in the cold-component: to avoid potential confusion we will quote our results below in terms of the fraction $f_h$ of the intrinsic population in the hot-component. We initially adopt the best-fit values for the classical population as reported in Brown (2001): $\sigma_c = 2.2, \sigma_h = 17.0$ and $f_h = .8$.

To test this inclination distribution using our survey simulator approach we require a complete description of the distribution of all six orbital elements. We combined Brown’s two component inclination distribution with a uniform $a/e$ distribution, bounded by $40 < a < 47$ AU and $q > 38$ AU, and uniform mean longitude, peri-center and node distributions (solid line in panel A of Figure 4). The Brown (2001) model provides a marginally acceptable match to the inclination distribution of the L3+Pre sample of main classical belt objects. The model $a$ and $e$ CDFs when observed through the survey simulator, however, do not match the L3+Pre sample at greater than 99.9% confidence level and thus we reject this model. The $a$, $e$ distributions of our 33 classical belt objects are not matched by a uniform $a$, $e$ distribution for the main classical belt. A more complex $a$, $e$ distribution is required.

5.1.2. The Semimajor Axis Distribution

A uniform distribution for the semimajor axis and eccentricity of classical main belt objects is strongly rejected by the L3+Pre sample. To find distributions that are more consistent with the L3+Pre sample we first adjusted the semimajor axis distribution to account for the presence of the destabilizing $v_8$ secular resonance (Knezevic et al. 1991; Duncan et al. 1995); the $v_8$ resonance rapidly removes objects on low inclination orbits with $a < 42$ AU. The semimajor axis location of the $v_8$ is constant until orbital inclination of about $i \gtrsim 12^\circ$ after which point the location of the $v_8$ quickly moves to smaller semimajor axis values: the $v_8$ has little effect on $a \sim 42$ and $i \gtrsim 12$ orbits. We use a semimajor axis distribution that is uniform in $a$ but with orbits in the $a < 42, i < 12$ region removed to emulate the structure of this destabilizing resonance. This is similar to the structure previously noted by Jewitt et al. (1998) but here we note the inclination dependence of this semimajor axis boundary.

Unfortunately, for these models (where the $a$ range of the low-inclination members of the main classical belt is sculpted by the $v_8$) the $a$ distribution is still rejected at the +99% level when compared to our L3+Pre observations (dotted curve in panel B of Figure 4).

An examination of the $a/e/i$ distribution of known KBOs reveals what appears to be a dearth of low-e objects beyond $a \sim 45$ AU. Guided by this observations we examined models where the cold-component of the main classical Kuiper Belt has some maximum semimajor axis $a_{\text{max}}$ and an inner boundary caused by the $v_8$ resonance. The value $a_{\text{max}}$ was adjusted until the $a$ distribution of our model, observed through the survey simulator, was not rejected by the L3+Pre sample at more than the 95% level. Following this procedure we find

Figure 4. L3+Pre objects (histogram) compared to various models of the $a$ (left panels), $e$ (middle panels) and $i$ (right panel) distributions as observed through our survey simulator. Panel A: dotted line is the model from Jones et al. (2006) (rejected); solid line is Jones et al. model with a bimodal inclination distribution from Brown (2001) (rejected); Panel B: dotted line is the Jones et al. model with bimodal inclination and $a$ distribution modified to account for the presence of the $v_8$ resonance (rejected); solid line same as dotted line but with a restricted $a$ range for the cold classical Kuiper Belt (accepted). Panel C: dotted line, same model as Panel B but with inclination distribution parameters chosen to minimize the AD statistic of the inclination distribution (accepted); solid line is the same model but with the eccentricity distribution of the cold-component weighted to lower values of $e$ (accepted, best fit model). See Section 5.1 of text.
We find a significant deficit of cold main classical Kuiper Belt objects with $a > 45$ AU and find that a uniform $a$ distribution for the cold main classical Kuiper Belt is formally rejected for semimajor axis drawn from outside the range $42.4 < a < 46.2$ AU. Further, we find that our AD and KKS statistics are minimized (i.e., provide the best match between the model and observer Kuiper Belt) for $a_{\text{max}} \sim 45$ AU. We conclude that the cold-component of the main classical Kuiper Belt (essentially the cold-component of the entire Kuiper Belt) ends just beyond $a \simeq 45$ AU. For our modeling and population estimates we hereafter take the cold-component of the main classical belt to occupy only the $42.5 < a < 45$ AU zone (solid line in panel c of Figure 4).

5.1.3. The Eccentricity Distribution

In the preceding model examination the eccentricity distribution was $P(e) \propto e$ as suggested in Jones et al. (2006). While not formally rejected by the observations, the match between the observed and survey simulator eccentricity CDFs is not a particularly good match (dotted line in panel c of Figure 4). The level of disagreement is enhanced when we modify our choice of an inclination distribution that better match the L3+Pre sample, indicating a clear connection between the eccentricity and inclination distributions. An examination of the eccentricity distributions of the low ($i < 5$) and high ($i > 5$) inclination members of the main classical belt reveals that the low inclination main classical belt objects have an $e$ distribution that is slightly weighted to lower values, when compared to the main classical belt members with larger values of inclination.

A uniform eccentricity distribution for the cold main classical belt provides an intrinsic orbit distribution that, when observed through the survey simulator, provides a much better match to the L3+Pre sample (solid line in panel B of Figure 4). While a uniform $e$ distribution is not particularly physical (the phase magnitude from an exponential distribution with $\alpha = 0.72$.

Each such drawn object is then passed through the CFEPS survey simulator to determine if it would have been detected and tracked. The orbital-element distribution for a large number of simulated tracked objects is then compared to that of the L3+Pre tracked objects that satisfy the constraints ($40 < a < 47$ AU and $q > 38$ AU). This restriction on $q$ is needed since our current sample is too small to allow us to accurately model the complex stable phase space in the $35 < q < 38$ AU zone.

We ran a grid of 2050 models using the above prescription covering a range of $(f_h, \sigma_h)$ pairs, constrained to the value of $\sigma_e = 2.2$ from Brown (2001) and the $a/e$ distributions as described above. We take as our “best fit” those model parameters $(f_h$ and $\sigma_h)$ for which the AD statistic of the $i, q$ and $r$ distributions is minimized. We find our best-fit models is $f_h = 0.6$ and $\sigma_h = 15^\circ$. Our “confidence boundaries” are given by those parameters which produce models with $i, q$ and $r$ AD statistics that are smaller than 68%, 95%, and 99% of the bootstrapped values of the statistics, Figure 5. The contours of Figure 5 explore, in essence, the range of plausible $f_h$ and $\sigma_h$ parameters for our intrinsic model when tested against the L3+Pre sample.

An examination of Figure 5 reveals that our current sample only weakly constrains the width of the main-belt’s hot component. This poor constraint is a reflection of the small number of large-inclination objects in our current sample, along with the fact that a given discovery cannot be uniquely assigned to either of these two overlapping components.

If our “thick” model of Figure 5 applies, then based on our survey simulator analysis, all objects in our L3+Pre sample with $i < 10^\circ$ are more likely to be hot-component objects (in the large- $i$ tail of that population) than hot-component members. Thus, in a thick hot-component model, our current sample likely contains only two objects from the hot population and these two TNOs provide only a weak constraint on the hot component’s width. If one were to (unjustifiably) assign all the $i > 7^\circ$ TNOs to the hot population, the thick model can be rejected at $>99\%$ confidence. Thus, although external evidence (from other surveys) suggests that $\sigma_h \simeq 15^\circ$, our current sample provides only a loose confirmation of this result.

In our modeling we have not explored the relation between the hot main classical Kuiper Belt and detached component of the belt which has $e > 0.24$ and $a > 50$ AU. Our current statistics on the distant belt are very limited, however the $a > 50$ AU detached component of the Kuiper Belt may actually be the extension of the hot main classical belt.

5.1.5. Population Estimates

Following the procedure described in Section 4.3, and using the best fit parameters described in the proceeding sections, we
compute a population estimate for the main classical belt, giving (see Table 5):

\[ N_{\text{classical}}(H_g < 10.0) = (120^{+50}_{-60}) \times 10^3 \]

where the uncertainties reflect a 95% confidence limit assuming the underlying orbital model and its parameter values are correct. This population estimate is model dependent, and varies strongly with the width \( \sigma_h \) of the hot-component. As seen in Figure 5, increasing \( \sigma_h \) requires a larger fraction of hot-component objects, which increases the population needed to match the observations. This is due to the detection bias against finding hot objects in an ecliptic survey. As a comparison, Table 7 gives the population estimates derived from two other models within the 95% contour. For a “thin disk” model we take the the parameters that minimize the fractional size of the hot population, \( \sigma_h = 10^\circ \) and \( f_h = 0.2 \), which produces a population estimate, for the hot-component, that is slightly more than half our best-fit model estimate. For a “thick disk” model we take the acceptable model with \( f_h \sim 0.7 \) which gives a population estimate 2-sigma larger than the estimate based on our best-fit parameters. In all three cases the inclination distribution of the cold-component is held constant at \( \alpha_c = 2:2 \) and we note that the total cold population (which is \((1 - f_h) \times N(H_g < 10)) \) ranges between 50,000–60,000 for these models. Unsurprisingly the total size of the better-sampled cold population is relatively well determined (\( \sim 10\% \)), while the poorly sampled hot-component contains most of the uncertainty (factors of several).

Figure 6 shows a representation of our underlying model relative to the real L3+Pre detections and a set of simulated detections. In the classical belt’s \( a = 45–47 \) AU region the survey simulator produces few detections and those that do occur have large eccentricities due to the perihelion flux bias (see also Jones et al. 2006).

### Notes.

Estimates are given for our model for each subpopulation within the Kuiper Belt. The values in the upper and lower columns are the upper and lower bounds on our 2-\( \sigma \) confidence region for the model-dependent population estimate. All values are in thousands of objects. The Kozai subpopulation shows how forcing half of all plutinos with \( i > 15^\circ \) to librate in the Kozai resonance causes a small increase in the population estimate.

5.2. The Plutinos (3:2 Resonant Objects)

There are eight plutinos in the L3+Pre sample. The plutino population is of historical importance as the first recognized resonant subpopulation of the Kuiper Belt (Tholen et al. 1994), and is by far the most numerous in the flux-limited observational catalogs. Plutinos are forced by their resonant argument (e.g., Malhotra 1995, 1996) to come to perihelion away from Neptune (precisely \( \pm 90^\circ \) for a zero libration-amplitude plutino).

Compared to the non-resonant objects, modeling the plutino population is complicated by the need to respect the longitude relations embodied in the resonant argument. For objects in 3:2 mean motion resonance with Neptune the resonant angle \( \phi_{32} \) has the form:

\[ \phi_{32} = 3\lambda - 2\lambda_N - \sigma \]

where \( \lambda \) and \( \sigma \) are the object’s mean longitude and longitude of perihelion and \( \lambda_N \) is Neptune’s mean longitude.

Plutinos librating in the resonance will have their resonant angle \( \phi_{32} \) librate around \( 180^\circ \) with some amplitude \( L_{32} \). For example, Pluto’s resonant angle has a libration amplitude of \( L_{32} \approx 84^\circ \) (Milani et al. 1989). At maximum libration, the angle between the pericenter direction of Pluto (i.e., \( \lambda = \sigma \)) and Neptune is \((180^\circ - 84^\circ)/2 = 48^\circ \) or \((180^\circ + 84^\circ)/2 = 132^\circ \); at these extrema the librating relative perihelion longitude reverses direction. This inability to approach Neptune causes the “hole” seen in the on-ecliptic projection of Figure 7.

The resonant argument, \( \phi_{32} \), oscillates sinusoidally around \( 180^\circ \), thus passing more time at the two extrema \( \phi_{32} \pm L_{32} \) than near \( 180^\circ \) itself. The observational impact of this effect is that objects with libration amplitudes of \( L_{32} \) have a bias to being found near \((180 \pm L_{32})/2 \) degrees of longitude away from Neptune. Flux bias weights against the discovery of plutinos far from their current pericenter locations, and so when looking at a particular longitude from Neptune one will tend to find more objects for whom the observed longitude relative to Neptune is such that their resonant argument is at the extrema.

The L3 plutinos have libration amplitudes similar to the longitudes for...
Figure 6. Semimajor axis (a) vs. eccentricity (e) and inclination (i) for the main classical belt objects. Filled squares represent the CFEPS L3+Pre sample, the dotted points represent the intrinsic population of the main classical belt, taken from our nominal model. (A color version of this figure is available in the online journal.)

Figure 7. A planer view of the L3+Pre tracked plutino sample, discovery field location and intrinsic plutino population. The gray area represent the intrinsic Kuiper Belt population produced by our nominal model for the plutino population. The circles are at the discovery locations of our L3+Pre plutinos. For each L3+Pre field we present a box that encloses the approximate boundaries of the region of the solar system that survey was sensitive to. The inner boundary (20 AU) is set by the rate cut in our detection pipeline while the outer limit is set by our flux limit and is drawn at the distance exterior to which we are no longer sensitive to objects with $H_g > 7.5(D_p \lesssim 200$ km).

where they were found. In practice plutinos have $L_{32} < 130^\circ$, and so no plutino can be at pericenter in fields that are close to the direction (or antidirection) of Neptune, explaining why the Presurvey, L3q and L3y blocks yielded no plutinos (see Table 1 and Figure 7).

Because of the $1/r^2$ nature of the reflected flux and the strong bias to detection at certain longitudes, correct modeling of the plutino population requires knowledge of the ecliptic longitudes and flux limits of the surveys. The change in distance from perihelion to aphelion for an $e \approx 0.25$ plutino (30–50 AU) drops its apparent magnitude by $\Delta m = 2$ magnitudes. Because of the slope of the luminosity function, this change in flux causes a drop by a factor of $10^{\alpha \Delta m} \approx 30$ in the plutino fraction at longitudes where they are preferentially at aphelion. The dependence of the heliocentric distances at detection on the size distribution is illustrated in Figure 8; if the size distribution is flatter a larger fraction of objects above the flux limit are found at larger distance. The median detection distance varies by more than 2 AU if the power law $H$-magnitude distribution spans the range of values given in the literature. Therefore, one cannot determine the size distribution of the plutinos from surveys that cover a range of solar longitudes unless one knows the ecliptic longitude of the surveys where plutinos were both detected and not detected. Our characterized survey provides this information, but with only 8 plutinos in the L3+Pre sample, we cannot uniquely constrain this large parameter space since the detected $r$ distribution also depends on the $e$ and $\phi_{32}$ distributions.

We proceeded to find a satisfactory model of the intrinsic plutino orbital element distribution in a two-step process. First we produce hypothetical parametric representations of the intrinsic orbital-element distributions based on available
observations and dynamical modeling and then we make small adjustments to these distributions until they are not rejected by the L3+Pre sample.

The \( a, e \) limits are taken as the borders of the stable resonance (Morbidelli 1997). A Gaussian \( e \)-distribution with mean of 0.21 and standard deviation of 0.06 provides a reasonable match to the observed eccentricity distribution of the plutinos listed in the 3:2 SSBN07 classification (Gladman et al. 2008) and provides an initial model for this element (i.e., we use eccentricity distribution of the MPC reported plutino detections as a proxy for the intrinsic one, with no attempt to correct for detection biases).

Brown (2001) concluded that a single component Gaussian inclination distribution of width \( 10^\circ \) degrees satisfactorily represented that plutino population, so we begin with this 10-degree width.

The libration amplitude, \( L_{32} \), distribution is taken to be a match to the compilation of Lykawka & Mukai (2007); a symmetric “triangle” where the most likely value is \( 65^\circ \), falling to zero at \( 0^\circ \) and \( 130^\circ \). The resonant angle \( \phi_{32} \) cannot be chosen uniformly in the range \((180 - L_{32}, 180 + L_{32})\) since \( \phi_{32} \) oscillates sinusoidally in this range; accordingly, we time-weight the \( \phi_{32} \) oscillation when producing our model distribution of plutinos. Longitudes of node and mean anomalies were chosen randomly. Having picked a resonant angle \( \phi_{32} \), Equation (6) then forces the value of the plutino’s longitude of perihelion \( \sigma \).

This straightforward model produced \( a/e \) and distance at detections distributions that are rejected at better than the 99% confidence and an inclination distribution rejected at the 95% confidence level (see Figure 9). To first order the inclination distribution is not strongly coupled to the other distributions, so we proceed by first searching for models that reproduce the observed inclination distribution and then focus on determining the \((a, e)\) and libration amplitude distributions.

5.2.1. The Inclination Distribution of the Plutinos

The CDF of the 8 L3+Pre plutino inclinations is more extended than would be anticipated given a Gaussian of width \( 10^\circ \); the observed population has only a \( \sim 5\% \) chance of being drawn from such an intrinsic distribution. Increasing the intrinsic width of the plutino inclination distribution to \( 15^\circ \) provides a more reasonable match, and is intriguingly similar to the width we favor for the hot classical belt. Further widening the inclination distribution to \( 19^\circ \) is once again rejected at the 95% confidence level.

That the plutino population appears to have an inclination distribution similar to that of the hot-component of the classical main belt is a cosmogenically intriguing result. The other resonances may also share this inclination distribution but the sample of resonant objects in the L3+Pre sample is not large enough to allow us to explore this possibility.

The three highest-inclination L3+Pre plutinos (of 8) are in fact the three highest-inclination plutinos of the entire MPC “on-ecliptic” catalog. We hypothesize (but cannot prove) a historical bias against the tracking of large-\( i \) plutinos discovered in the ecliptic, which may have been initially given larger \( e \) (to make SDO orbits) in order to generate the out-of-ecliptic component of their observed motion, resulting in them being lost in subsequent tracking. The lack of high-inclination plutinos in the MPC catalog may thus be partially an artifact of ephemeris bias.

We also examined models where the inclination distribution of the Plutino population matched that of the main classical belt: We find that the Plutino models with the same two component inclination distribution as the main classical Kuiper Belt fail to match the L3+Pre sample and are rejected at more than the 99% confidence level. We conclude that the apparently large fraction of low-\( i \) plutinos in the MPC catalog is dominantly due to the bias inherent to looking in the ecliptic.

We caution that a complete model of the plutino populations inclination distribution should take into account the fact that Pluto and some other plutinos are also in the Kozai resonance (Morbidelli 1997), keeping their perihelia (and hence point of maximum detectability) out of the ecliptic plane. This effect generates a very complicated relation between the Kozai fraction and the longitude of the surveys. None of our eight L3+Pre plutinos are librating in the Kozai resonance; in Section 5.2.4 we discuss the impact of this plutino subpopulation on our population estimates.

5.2.2. The \( a/e \) and Libration Amplitude Distributions

The reason for our discordance with the straightforward \( a/e \) and libration amplitude distribution is simple to understand; detection biases favor discoveries in certain parts of the plutino orbital-element space. In particular, detection of large-\( e \) plutinos is heavily favored, resulting in them being over-represented in the MPC catalog. Our survey simulator shows that the “MPC \( e \) distribution” would result in \( \sim 40\% \) of our L3+Pre plutinos being detected closer than our closest real detection. We are forced to conclude that the intrinsic plutino \( e \)-distribution is more concentrated to lower values. With only eight L3+Pre plutinos, we cannot accurately determine the true eccentricity
Another detection bias present in all samples of plutinos is the correlation between observed libration amplitude and the longitude relative to Neptune of the survey field. Thus, although not likely particularly representative of the entire plutino population, we use a libration amplitude distribution modeled after our own detections (most of our plutinos have $L_{32}$ near 60 or 100 degrees; such objects are favored at the longitudes of our blocks). This model yields an acceptable match (Figure 9) to the L3+Pre detections; that is, we cannot reject the model even if we are also sure that there are detection biases in the angular variables affecting the detected libration amplitudes.

We also examined the result of a flat libration-amplitude distribution ($L_{32}$ uniform to a maximum value of 130°). This clearly worsened the match and can be rejected at the 99% confidence level. Therefore, the gross characteristic of the detected MPC sample, that the libration amplitudes below 50 degrees and above 110 degrees are depleted (Lykawka & Mukai 2007) appears to be correct, although the functional form of the intrinsic distribution is still poorly constrained.

5.2.3. The Plutino Size Distribution

Both the Hahn & Malhotra (2005) and Elliot et al. (2005) studies suggested the possibility that the plutino size-distribution might be flatter ($\alpha = 0.52–0.54$) than the rest of the belt. The survey simulator produces poorer matches in the detected distance distribution if we use these lower values of $\alpha$ (i.e., a flatter slope for the plutino size distribution) (see middle panel of Figure 9). Essentially a flat slope implies an increased fraction of large plutinos would be detected at greater heliocentric distances. Thus the distance distribution would have a larger fraction of $r > 40$ AU detections. With only eight L3+Pre plutinos, the survey simulator does not formally reject such a flat $H$-slope, but such shallow size distributions are found to be less likely and we thus choose to use the same size distribution for the plutino sample as has been determined for the main classical Kuiper Belt, $\alpha = 0.72$.

5.2.4. Population Estimate

Our nominal model yields an estimated plutino population

$$N_{\text{plutino}}(H_g < 10.0) = 25^{+25}_{-12} \times 10^3 (5)$$

(95% confidence, model dependent) as the total plutino population (Table 7).

With only eight detected plutinos, our population estimates are only good to about a factor of two due to the large parameter space which affects detectability. For example, although none of our eight L3 plutinos librate in the Kozai resonance, other
high-inclination plutinos do (Lykawka & Mukai 2007). If we assume half of the plutinos with \( i > 15^\circ \) have their arguments of pericenter librate around 90 or 270 degrees with a width of 50 degrees, then we can increase the estimated population of plutinos to \(~ 30000\) (Table 7) without violating the lack of a Kozai population in the L3+Pre sample. This occurs because only a few of the L3 blocks probe the longitudes where these plutinos would cross the ecliptic and those that did cross our field of view would not be at pericenter and thus harder to detect. This further reinforces the need for knowledge of the survey longitudes in order to estimate the size of resonant populations.

Changing the nominal model by flattening the size distribution to \( \alpha = 0.54 \) causes the population estimate to drop substantially to \( N(H_g < 10)12,000 \), since the plutinos are detectable at greater distances.

Given all the model dependencies, we conclude that the plutino population is \(~ 25,000\) objects with \( H_g < 10 \), to a factor of 2. The nominal estimate indicates that the intrinsic plutino fraction is about 20% of the main classical belt, whose estimate is also uncertain to a factor of 2. Since the majority of Kuiper Belt surveys have been conducted near the ecliptic plane, the fact that the plutino population lacks a cold-component results in an apparent plutino fraction (relative to the classical belt) in the MPC catalog being smaller than the intrinsic one, a fact that some readers may find counter intuitive.

The only previous published plutino population estimate, based on analysis of a KBO survey (Trujillo et al. 2001) is \( N(D_p > 100) = 1400 \), accurate to a factor of two. Converting our estimate to the same size limit assuming albedo of 0.04 yields an estimate of 9,000, also to a factor of two precision (neglecting the albedo uncertainty). Clearly we estimate a significantly larger plutino population; this is result is due to the fact that the plutino “bias corrections” applied previously assumed the same inclination distribution for the plutinos as for the classical belt. Lacking a cold-component the plutino population is relatively less detectable than the classical belt. We estimate that the plutino population is 40%–50% as numerous as the cold classical main belt population.

The large fraction of plutinos, compared to the main classical belt seems to indicate that Neptune did, at some point, have a slow migration phase which allowed the 3:2 resonance to sweep up a substantial population, although quantitative estimates of the ratio of plutinos to classical objects is lacking except in Hahn & Malhotra (2005). The lack of a low-inclination component in the plutino population, however, appears to be a critical problem for the concept of slow migration into a cold disk.

### 5.3. The Inner Classical Belt

The inner classical belt is defined as the non-resonant, non-scattering orbits with semimajor axes between Neptune and the 3:2 resonance (Gladman et al. 2008). Duncan et al. (1995) first showed, via long-term numerical simulation, that interior to the \( a = 39.4 \) AU semimajor axis of the 3:2, there is a region of orbital stability (from \( a \approx 36–39 \) at low e), and remarked with surprise that no objects were known in that region. Petit & Gladman (2003) suggested that the lack of such objects could be due to systematic follow-up bias in early surveys, and showed a handful of such objects derived from more systematic tracking campaigns. Kavelaars et al. (2008) and Parker et al. (2007) discuss this tracking bias in more detail.

Based on current observations and numerical-stability simulations the number of inner classical belt objects is anticipated to be low since the volume of phase space available is much smaller than for the main classical belt. In Gladman et al. (2008), 16 of the 510 TNOs (3%) are classified as inner classical belt objects, which is in rough agreement with our having two such discoveries in the 63-object L3+Pre catalog (L3w06 and L3y14PD). With only two characterized detections we currently provide only a rough population estimate based on a simple phase-space model and must leave exploring the internal orbital structure of this region for the future.

Guided by the results of Duncan et al. (1995) and unpublished integrations by one of the authors (B. Gladman), we have modeled the inner classical belt with the following algorithm. The \( a/q \) elements are uniformly distributed in the region \( a = 37–39 \) AU and \( q > 35.3 \) AU. We choose orbital inclinations uniformly from the same double-Gaussian inclination model as for our nominal classical main belt model, \( \sigma_c = 2:2, \sigma_h = 15^\circ, \) and \( f_h = 0.6 \) (see Section 5.1), except that we exclude the region \( 7^\circ < i < 22^\circ \) in order to account for the strong destabilizing presence of the \( 8^\circ \) secular resonance which passes through the inner classical belt at these inclinations (Knezevic et al. 1991; Duncan et al. 1995). The angles \( \omega, \Omega, \) and \( M \) are uniformly distributed between (0,360) degrees.

The number of inner classical belt objects is estimated, subject to our model constraints, using the procedure described in Section 4.3. We find the inner classical belt population to be (see Table 7)

\[
N_{\text{inner}}(H_g < 10) = 2200^{+5000}_{-1900}
\]

The uncertainty range is the 95% confidence region and is model dependent. The large range of uncertainty is due to the presence of only two detections in the L3+Pre sample. Our two L3+Pre inner-belt detections both have low-\( i (i < 5^\circ) \) inclinations. For the two component \( i \)-distribution given above, the “hole” caused by the \( 8^\circ \) resonance results in a very low fraction of detected hot-component inner classical belt TNOs in an ecliptic survey. We calculate that if there is a cold-component then the cold inner-belters should make up \(~ 96\% \) of the inner-belt CFEPS detections. If, however, the inner belt has only a hot population then low-\( i (i < 5^\circ) \) KBOs still represent \(~ 70\% \) of the expected detections. Under the assumption of a hot only model, (i.e., \( f_h = 1 \) ) the size of the intrinsic population required to match the L3+Pre sample would quadruple (Table 7) due to the lower detectability of the intrinsic population. Our 2 low-inclination detections are, of course, consistent with either of these hypothesis.

If we use the CFEPS L3+Pre survey simulations as a proxy for generic KBO surveys conducted near the ecliptic then we might expect the MPC fraction of low and high inclination inner-belt objects discovered near the ecliptic would match that of the simulator. This simulator by proxy approach is not too risky, since the non-resonant objects obey no phase relationship with Neptune. Of the 11 inner classical belt objects in the MPC database (Gladman et al. 2008) that were discovered within \( 2^\circ \) of the ecliptic, 7 have inclinations of less than \( 5^\circ \). This 64% ratio is close to that expected for an inner-belt containing no cold-component (70%) and in (mild) conflict with the two component model (90%), leading us to suggest that the inner classical belt consists of a purely hot inclination population.

We are cautious not to draw too strong a conclusion from this examination of the MPC database since we expect that inner-belt objects with small inclinations may have been mistakenly classified as plutinos and lost, biasing the MPC against low-\( i \) inner-belters. Even with these uncertainties, the inner-belt population is unlikely to exceed 2% of the classical belt.
6. DISCUSSION

The L3+Pre sample provides a number of new insights into the orbital structures of the Kuiper Belt. We have presented in the preceding sections some quantifiable measure of that orbital structure. In what follows we provide a general interpretation of our observations in light of the current literature on Kuiper Belt formation.

6.1. The Outer Edge of the Main Classical Belt

Based on the L3 sample we have determined that the cold- and hot-components of the main classical belt have distinct eccentricity and semimajor axis distributions. Our modeling of the orbit distribution indicates that the cold main classical belt is isolated in semimajor axis and likely does not extend the full distance to the 2:1 resonance; the cold belt appears to end at ~ 46 AU.

Migration models (see Hahn & Malhotra 2005; Chiang et al. 2003; Gomes et al. 2004, for example) produce outer edges to the cold and hot populations by using an initially truncated disk (usually with a pre-migration edge well interior to the current 47.4 AU location of the 2:1 resonance). Many of these models have sought primarily to generate an outer edge at \( a = 47.4 \) AU. The fact that we have found different edges (in semimajor axis space, which makes for a fuzzy edge in heliocentric distance) for the hot and cold populations is a new constraint for formation models.

In some outer solar system formation model the radial extent of the cold disk arises as a consequence of the time-scale for the damping of Neptune's eccentricity (see Levison et al. 2008, for example) while the extent of Neptune's migration is controlled by initial radial extent of the planetesimal belt of the solar system (Gomes et al. 2004). Alternatively, the cold classical main Kuiper Belt could be the in situ remains of the primordial solar system and the extent of this population may be indicating the edge of primordial disk. Regardless, formation scenarios are now left to the challenge of producing a cold core whose eccentricity and semimajor axis distributions are distinct from the hot population.

6.2. The Primordial Kuiper Belt

The separate eccentricity and semimajor axis distribution of the hot and cold main classical belt populations add to the growing number of compelling observational differences: different colors (Tegler & Romanishin 1998), different binary fractions (Stephens & Noll 2006), different albedos (Grundy et al. 2005), and perhaps different size distributions (Bernstein et al. 2004; Elliot et al. 2005). Together these imply that the two populations had separate formation locations or processes. Based on the dynamics of the cold-component we feel it likely that this population formed in situ and are more comfortable with models that transfer the hot-component from some other region of the solar system.

The hot main classical belt population has an eccentricity distribution considerably hotter than that of the cold-component, with a semimajor axes distribution that does not exhibit the restriction of the cold-component. Intriguingly, we believe it plausible that the hot-component has the same inclination distribution in the inner classical belt, main classical belt, plutino population, and perhaps other populations not modeled here due to lack of detections.

The hot main classical belt distribution is, in our opinion, compellingly like the high-inclination population produced in Levison et al. (2008) and also somewhat similar to that of Hahn & Malhotra (2005). Testing these models quantitatively will require passing the results of the model simulations through the CFEPS simulator and comparing the resulting orbital distributions to the CFEPS L3+Pre detections. To facilitate quantitative comparison of models with the CFEPS results, the authors provide full details of the survey simulator on the CFEPS Web site (http://www.cfeps.net).

Examining the distribution of MPC inner belters lends evidence to our suggestion that the inner belt lacks a low-inclination component. The authors are not aware of any outer solar system model that predicts a change in the inclination distribution between the inner and main classical belts. Additional evidence for the hot-component membership of the inner belt could come from a census of the colors of the members of this population.

Models of resonance capture during a smooth Neptune migration (Malhotra 1993) indicate that if the large eccentricities of current plutinos are the result of “eccentricity pumping” during resonance migration, the 3:2 resonance must have swept through the inner belt. Resonance capture alone, however, does not strongly affect the inclinations of captured objects (Gomes 2003; Hahn & Malhotra 2005). Thus, if the inner belt had a low-inclination component during the putative resonance sweeping, they should have been easily captured and we should find this cold (low-\( i \)) population in the current plutino population; it seems not to be there today. Based on this reasoning, we postulate that the inner belt never had a low-inclination component or it was removed prior to the resonance sweeping migration of Neptune.

In the so-called “Nice” model (Levison et al. 2008) the low-inclination component of the main classical belt is produced by resonance overlap and diffusion in the zone between Neptune and the 2:1 resonance. This mechanism may be very effective at creating a low-\( i \) component in the inner belt or at least appears to produce an inner belt with the same inclination distribution as the main classical belt (see Figures 6, 9, and 10 in Levison et al. 2008). More detailed modeling of this scenario and additional observations are needed before a conclusion can be drawn regarding the structure of the inner belt region predicted.

6.3. Plutinos and the Jupiter Family Comets

Is our estimated plutino population large enough to be the source of the Jupiter-family comets (JFCs)? Levison & Duncan (1997) examined the JFC supply problem from the Kuiper Belt as a whole and Morbidelli (1997) quantitatively explored the hypothesis of the gradual gravitational erosion of the plutino population as a supply source for the JFCs and estimated that there would need to be ~ \( 4.5 \times 10^7 \) objects currently in the 3:2 resonance for this population to be a major source of JFCs.

Our estimate of the plutino population, \( N(H_p < 10) \sim 3 \times 10^5 \), must be scaled by the size-distribution relation to compare with the estimate from Morbidelli (1997). We take, as a plausible estimate, the size of a typical JFC to be \( D \sim 5 \) km (Fernández et al. 1999). Using Equation (4) with an albedo of \( p_v = 0.05 \) gives \( H_p \sim 15.7 \) for a typical, \( D \sim 5 \) km, JFC resulting in \( \Delta H_p = 5.7 \) between the JFC size and the size limit of our population estimate; assuming a uniform power law for the plutino luminosity function with \( \alpha = 0.72 \) implies an intrinsic
population of $N(d > 5 \text{ km}) = 4 \times 10^8$ plutinos, resulting in the plutinos being a plausible source for the JFC population.

Due to ambiguities in the size distribution slope, the location at which the steep size slope for large objects rolls over to a shallower slope (Bernstein et al. 2004; Petit et al. 2006; Fraser et al. 2008) and the true size of a typical JFC, these numbers should be treated with caution. For example, if JFCs are 10 km rather than 5 km, the corresponding 3:2 population of 3 $\times 10^7$ objects is insufficient as a supply source.

The sensitivity of these numbers to the unknown value of the typical JFC size is especially worrying, and results in little confidence in a conclusion either for or against a resonant source; we remark that if a resonant source were thought plausible, the now-realized abundant population of objects in high-order resonances beyond the 3:2 (Hahn & Malhotra 2005; Gladman et al. 2008; Lykawka & Mukai 2007) must be seriously examined as an additional source of gradually destabilized objects which might rival or exceed the 3:2 alone. Arguments favoring the scattering disk as the most likely source of the JFCs (Duncan & Levison 1997) continue to be appealing. Lastly, if either the size distribution of plutinos is shallower, $\alpha \sim 0.52$ (Elliot et al. 2005; Hahn & Malhotra 2005) or if the size distribution rolls over to some flat slope as expected then the number of small plutinos drops by a factor of 10 and there are many orders of magnitude too few plutinos available to act as the source of JFCs.

7. CONCLUSIONS

Based on modeling the L3+Pre sample with the CFEPS survey simulator, we conclude:

1. The inner classical belt is roughly $\sim 2$%–5% of the population of the main classical belt. The inner classical belt is most likely devoid of a cold-component, but further observations and modeling are needed before the absence of a cold-component can be established.

2. The cold classical main Kuiper Belt is a low-$i$, low-$e$ component tucked into the 42.5 $< a < 46$ AU zone. The cold-component represents about 40% of the classical main Kuiper Belt population. Models where the semimajor axis distribution of cold-belters is uniform and extends beyond 46.2 AU are rejected at the 95% confidence level. The eccentricities distribution of this component appears to be weighted towards lower values.

3. The hot classical main Kuiper Belt contains a population of objects weighted towards large $e$ ($P(e \propto e)$ and drawn from a broad inclination distribution well-represented by a Gaussian of width $\sigma_h \sim 15^\circ$. In fact, this hot belt appears to uniformly fill the stable orbital phase-space between 35 and 47 AU and the detached objects may be the smooth extension of this population to larger $a$. Current CFEPS observations do not place strong limits on the semimajor axis range of the hot-component of the belt. The hot population represents about 60% of the classical main Kuiper Belt (nonresonant, nonscattering objects between the 3:2 and 2:1 Neptune resonances).

4. The 3:2 resonators appear to have an inclination distribution that matches the hot main classical belt and an eccentricity distribution centered around $e \sim 0.2$, consistent with stability estimates (Wan & Huang 2001). This population appears to be $\sim 15\%$ of the size of the main classical belt population, although this estimate is highly model dependent.

We have demonstrated the strength of utilizing the CFEPS Survey Simulator to interpret models of the Kuiper Belt’s underlying populations. Future Kuiper Belt surveys that provide the detection and tracking details to feed into such a simulator will provide greatly enhanced constraints on the detailed structure of this region of the solar system. We anticipate that the L4 and L5 CFEPS sample will be fully tracked by late-2009, roughly tripling the current L3+Pre sample.

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Facilities: CFHT (MegaPrime) CADC KPNO Palomar CTIO WHT

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