The Canada–France Ecliptic Plane Survey (CFEPS)—High-latitude Component

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11 Supporting material: Kuiper belt: general – surveys
12 Assigning an orbit to a dynamical class, as defined by Gladman et al. (2008).

Abstract

The High Ecliptic Latitude (HiLat) extension of the Canada–France Ecliptic Plane Survey (CFEPS), conducted from 2006 June to 2009 July, discovered a set of Trans-Neptunian objects (TN0s) that we report here. The HiLat component was designed to address one of the shortcomings of ecliptic surveys (like CFEPS), their low sensitivity to high-inclination objects. We searched 701 deg² of sky ranging from 12° to 85° ecliptic latitude and discovered 24 TN0s, with inclinations between 15° and 104°. This survey places a very strong constraint on the inclination distribution of the hot component of the classical Kuiper Belt, ruling out any possibility of a large intrinsic fraction of highly inclined orbits. Using the parameterization of Brown, the HiLat sample combined with CFEPS imposes a width 15° ≤ σ ≤ 15°, with a best match for σ = 14°. HiLat discovered the first retrograde TNO, 2008 KV42, with an almost polar orbit with inclination 104°, and (418993) = 2009 MS5, a scattering object with perihelion in the region of Saturn’s influence, with a ∼ 400 au and i = 68°.

Key words: Kuiper belt: general – surveys

1. Introduction

The Kuiper Belt is widely thought of as a leftover flattened disk of planetesimals extending from ~30 to 1000 au from the Sun. Several Kuiper Belt surveys broke ground by investigating the gross properties of the TNO diameter and orbital distributions via large samples (Jewitt et al. 1996; Gladman et al. 2001; Trujillo et al. 2001; Millis et al. 2002). It is now obvious that this region must have been heavily perturbed late in the process of giant planet formation. The Kuiper Belt’s small mass and the existence of many objects with large orbital inclinations (i up to 50°) indicate that a process either emptied most of the mass out of the primordial Kuiper Belt or, more dramatically, that the Kuiper Belt was transported to its current location during planetary migration. Recent models suggest stellar encounters (e.g., Levison et al. 2010; Brassier et al. 2012) or the existence of a ninth planet (Batygin & Brown 2016) may play an important role in shaping the outer solar system.

The dynamical structure of the Kuiper Belt is much more complex than anticipated by the community. Surveys with known high-precision detection efficiencies and that track essentially all their objects to avoid ephemeral bias (Kavelaars et al. 2008; Jones et al. 2010) are very efficient at disentangling these details and the cosmogonic information they provide. The Canada–France ecliptic plane survey (CFEPS)10 (Jones et al. 2006; Kavelaars et al. 2009; Petit et al. 2011, P1 hereafter), was a fully characterized11 survey that tracked more than 85% of its discoveries to orbit classification.12 Although discovering and tracking only 169 TN0s, this survey produced solid science contributions to Kuiper Belt science (P1; Jones et al. 2006; Kavelaars et al. 2009; Gladman et al. 2012). Without this accurate calibration and extensive tracking, surveys need to achieve a higher level of completeness to quantitatively constrain the orbital distribution of TNOs. In particular, tracking biases may cast doubts on the derived orbital distributions due to preferential loss of some dynamical classes (Jones et al. 2010).

The inclination distribution of the “main” Kuiper Belt is now recognized as bimodal (Brown 2001; Kavelaars et al. 2008), with a “cold” component of objects with an inclination width around 3° and a “hot” component with a very broad inclination distribution, much like the disk/halo structure of the galaxy. This discovery came at the same time as the realization that the cold component appears to have a different color distribution than the hot component (Doressoundiram et al. 2002; Tegler et al. 2003; Fraser & Brown 2012; Peixinho et al. 2015). The orbital distribution of these high-inclination objects has a huge lever arm on models of outer solar system formation and evolution, which include ideas like passing stars (Ida et al. 2000; Kenyon & Bromley 2004; Morbidelli & Levison 2004; Kaib et al. 2011b) that predict mean inclinations increasing with semimajor axis, rogue planets (Gladman & Chan 2006) that predict inclination decreasing with semimajor axis or transplanting almost all TNOs to their current locations during a large-scale reorganization of the planetary system (Thommes et al. 1999; Levison et al. 2008; Nesvorny 2015).

For both components, the distribution of orbital inclination can be modeled as $P(i) \sim \sin(i) \exp(-i^2/2\sigma^2)$ (Brown 2001).
The distribution of the hot component appears to have a Gaussian width $\sigma$ of at least $15^\circ$ (P1; Brown 2001; Kavelaars et al. 2009; Gulbis et al. 2010). A Lorentzian, with a similar shape, has also been used in place of the Gaussian (Gulbis et al. 2010; Adams et al. 2014), resulting in a similar inclination width of the hot population. Constraining the largest inclinations is difficult because detection biases in ecliptic surveys strongly disfavor their discovery. About two dozen TNOs with orbital inclinations in excess of $40^\circ$ are now known. Eris, the belt’s most massive known member (Brown et al. 2005), is in this group along with 2004 XR$_{190}$ (discovered by our group during CFEPS; Allen et al. 2006), the lowest $e$ orbit known TNO with a semimajor axis beyond 50 au (although $i \approx 47^\circ$).

Kuiper Belt objects with large inclinations spend the majority of their time at high ecliptic latitudes. As an example, Figure 1 shows the fraction of time spent by an object on a $50^\circ$ inclination orbit at various latitudes. Thus it is clear that a survey covering a patch of sky between $40^\circ$ and $50^\circ$ has a higher probability of detecting such an object than an ecliptic survey spanning the range $-5^\circ$ to $+5^\circ$. It follows that large-inclination objects are less represented in ecliptic surveys than in high-latitude surveys. Furthermore, it has become clear that the size distribution of the high-inclination component is flatter (number of objects increases more slowly when size decreases) than the ecliptic component (P1; Levison & Stern 2001; Bernstein et al. 2004; Fraser et al. 2014). Deeper surveys concentrating on the ecliptic will be increasingly dominated by low inclination objects. Another important factor in the efficiency of high-latitude surveys is the tracking effort. To determine the population to which an object belongs requires roughly five times more observing time than simply discovering it. CFEPS found about 200 objects, 10% of which have $i > 20^\circ$, similar to the number of discoveries in HiLat (see below). But the tracking effort for CFEPS, to avoid tracking bias, requires a time investment of a factor of $200 \times 5$ while it is only $20 \times 5$ for HiLat. Also, the largest inclination of CFEPS objects is $35^\circ$ to $2^\circ$, while HiLat had $30\%$ of its detections beyond this limit, with one object with an inclination of $68^\circ$ and another one at $103^\circ$. In the Minor Planet Centre (MPC) database, among the 45 objects with inclinations larger than $35^\circ$, $a > 30$ au (beyond Neptune), $q > 15$ au (lower limit for HiLat), and good orbit quality ($0 \leq U \leq 4$), more than half (26) have been discovered more than $10^\circ$ away from the ecliptic.

The situation at the end of 2006 was that a large fraction of the sky within a few degrees of the ecliptic had been covered by a few large surveys, with magnitude limits in the range of $m_R = 20$ to $23$. Being less sensitive to high-inclination objects (Figure 2), ecliptic surveys are less efficient at placing constraints on the width of the hot population. Thanks to two deep blocks of 11 deg$^2$ (one at $10^\circ$ and another at $20^\circ$ ecliptic latitude), the CFEPS efficiency decreases less than most other ecliptic surveys toward higher ecliptic latitudes. Still, although CFEPS prefers a hot population inclination width $\sigma$ of $16^\circ$, it could not reject a width of $25^\circ$. Actually, what limits the value of $\sigma$ is the relative decrease of the number of low- and intermediate-inclination objects when increasing $\sigma$, not the numerous high-inclination objects that are thus present. Using the converted Palomar Schmidt, Trujillo & Brown (2003) examined the majority of the northern sky to a depth of $m_R \sim 20.5$ (limit for median observing conditions), discovering several of the largest known objects; several of these large-inclination objects (like Eris) were close to the depth and motion limits of that survey due to their great distances. The ESSENCE Supernova Survey (Becker et al. 2008) announced the detection of 14 TNOs found in images covering $\sim 11$ deg$^2$ to $r' \sim 23.7$ in the ecliptic latitude range $-21^\circ$ to $-5^\circ$; this work also showed that once outside of the ecliptic core, the sky density is consistent with even a uniform distribution in latitude. Such a distribution would not be rejected by any characterized surveys known at the time. If
we relax the constraint of the functional form used by Brown (2001), CFEPS and other large-scale ecliptic surveys, like DES (Buie et al. 2003), can accept orbital distributions with a much larger population of high-inclination objects than our HiLat survey does, even if they all agree on the likely best representation.

We decided to perform a deep survey to magnitude $m_R \sim 23.5–24.0$ at high $(>12^\circ)$ ecliptic latitudes, called HiLat, to probe the hot component of the Kuiper Belt at sizes smaller than achieved by the Palomar wide area survey (Trujillo & Brown 2003) and SDSS. Although HiLat is insensitive to objects with inclinations below $10^\circ$ ecliptic latitude (Figure 2), it complements existing surveys because its design makes it very sensitive to objects having inclinations beyond $20^\circ–30^\circ$ (Figure 2). Clearly, ecliptic surveys have made great progress in describing the TNO populations and have paved the way for our HiLat survey, showing the need and importance of such a survey.

This manuscript describes the observations carried out during the six years of the project and provides our complete catalog (the HiLat release) of off-ecliptic detections and characterizations along with fully linked high-quality orbits. In summary, the “products” of the HiLat survey consist of four items:

1. a list of detected HiLat TNOs, associated with the sky location of discovery,
2. a characterization of each survey discovery observation (detection efficiency as a function of magnitude, motion on the sky; rate range searched; pointing of observations; etc.),
3. a survey simulator that takes a proposed Kuiper Belt model, exposes it to the known detection biases of the HiLat blocks, and produces simulated detections to be compared with the real detections, and
4. the updated CFEPS model populations accounting for the HiLat detections.

## 2. Observations and Initial Reductions

The HiLat project imaged $\sim$700 square degrees of sky from $12^\circ$ to $85^\circ$ ecliptic latitude (Figure 3) in its discovery phase. To discover new TNOs, we used the Canada–France–Hawaii Telescope (CFHT) MegaPrime camera in queue-mode operations to ensure an image quality (FWHM) of $0.5–0.9$ arcsec at discovery. For each pointing, we obtained a triplet of images 1 hr apart, each on the date listed in Table 1, and a nailing observation, a single image acquired a few nights away from the discovery triplet. The observations occurred in blocks of 11–32 contiguous fields, cycling three times between the fields. The number of fields observed in a series was chosen such as to have $\sim$1 hr between two consecutive observations of the same field. When a block was too large to be observed within one night, it was split into two sub-blocks observed during close-by nights, with similar observing conditions. All discovery imaging data is publicly available from the Canadian Astronomy Data Centre.13

The HiLat designation of a block was: a leading “HL” followed by the year of observations (6–9) and then a letter representing the two week period of the year in which the search observations were acquired (example: HL7 occurred in the second half of 2007 May), similar to CFEPS naming scheme. Discovery observations occurred between 2006 and 2008 June for the coverage below $60^\circ$ ecliptic latitude, followed by observations between $60^\circ$ and $85^\circ$ ecliptic latitude from 2009 May to July. This last part of the survey is simply named HL9 as it was acquired as 22 contiguous blocks over this time span.

The discovery fields were chosen in order to maximize our sensitivity to the latitude distribution of the Kuiper Belt, in particular the high-inclination TNOs. Observing at high ecliptic latitude ensured that we observed only high-inclination TNOs and greatly decreased the pressure for follow-up observations, as the number of TNOs per unit area drops sharply away from the ecliptic. The ecliptic longitudes were chosen to avoid the galactic plane and maximize our chances to get discovery and tracking observations (due to typical weather at the time of opposition for the discovery field and observing request pressure on the telescope). We used our Moving Object Pipeline (see Petit et al. 2004) to detect moving sources in our discovery blocks. A summary of the observing circumstances (pointings, image quality, detection thresholds) is given in Table 1. A large tracking effort occurred in the following years at CFHT and other facilities listed in Table 2. The observing strategy, both for discovery and follow-up, is similar to the one of CFEPS (Allen et al. 2006; Kavelaars et al. 2009; Petit et al. 2011). Our discovery and tracking observations were made using short exposures designed to maximize the efficiency of detection and tracking of the TNOs in the field. These observations do not provide the high-precision flux measurements necessary for possible taxonomic classification based on broadband colors of TNOs and we do not comment here on this aspect of the HiLat sample.

## 3. Sample Characterization

As is now the norm (Gladman et al. 1998, 2001; Jewitt et al. 1998; Trujillo & Jewitt 1998; Trujillo et al. 2000; Petit et al. 2006, 2011; Kavelaars et al. 2009), we inserted artificial sources in the images to determine the magnitude- and rate-
R.A. beyond the characterization limit, was not tracked to a high-quality orbit. The limiting magnitude of the survey, number of TNOs detected in the block, corresponding to a 40% efficiency below 40%. Since characterization is critical to our goals, we are unable to utilize the sample faint-ward of the design in the majority of cases. In Tables 3 and 4, we report dynamical classification in the Besançon TNO database14 with additional information such as dynamical classification and the correspondence between HiLat objects to the MPC. These data can also be found in the Besançon TNO database14 with additional information such as dynamical classification and the correspondence between HiLat objects to the MPC. These data can also be found in the Besançon TNO database14 with additional information such as dynamical classification and the correspondence between HiLat objects to the MPC. 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Table 2
Follow-up/Tracking Observations

| UT Date       | Telescope     | Obs. | UT Date       | Telescope     | Obs. |
|---------------|---------------|------|---------------|---------------|------|
| 2006 Nov 22   | WIYN 3.5 m    | 8    | 2008 Aug 31   | CFHT 3.5 m    | 6    |
| 2007 Apr 13   | CFHT 3.5 m    | 6    | 2008 Oct 22   | WIYN 3.5 m    | 9    |
| 2007 May 14   | Hale 5 m      | 13   | 2008 Dec 15   | Hale 5 m      | 13   |
| 2007 May 14   | KPNO 2.1 m    | 7    | 2008 Dec 20   | WIYN 3.5 m    | 17   |
| 2007 Jul 26   | CFHT 3.5 m    | 3    | 2009 Jan 26   | CFHT 3.5 m    | 7    |
| 2007 Sep 10   | WIYN 3.5 m    | 8    | 2009 Mar 25   | Subaru 8.2 m  | 2    |
| 2007 Sep 13   | CFHT 3.5 m    | 20   | 2009 Apr 22   | Subaru 8.2 m  | 5    |
| 2007 Sep 15   | Hale 5 m      | 25   | 2009 Jun 19   | WIYN 3.5 m    | 30   |
| 2007 Oct 07   | CFHT 3.5 m    | 6    | 2009 Jul 18   | CFHT 3.5 m    | 5    |
| 2007 Nov 08   | WIYN 3.5 m    | 17   | 2009 Jul 23   | Hale 5 m      | 31   |
| 2008 Mar 04   | CFHT 3.5 m    | 12   | 2009 Aug 17   | Hale 5 m      | 6    |
| 2008 Mar 08   | CFHT 3.5 m    | 3    | 2009 Aug 18   | CFHT 3.5 m    | 6    |
| 2008 Apr 04   | CFHT 3.5 m    | 10   | 2009 Sep 12   | CFHT 3.5 m    | 4    |
| 2008 May 02   | WIYN 3.5 m    | 21   | 2009 Sep 13   | CFHT 3.5 m    | 27   |
| 2008 May 05   | CFHT 3.5 m    | 21   | 2009 Oct 12   | CFHT 3.5 m    | 8    |
| 2008 May 28   | CFHT 3.5 m    | 14   | 2009 Nov 15   | CFHT 3.5 m    | 4    |
| 2008 Jun 01   | CFHT 3.5 m    | 3    | 2010 Jan 20   | CFHT 3.5 m    | 3    |
| 2008 Jun 07   | CTIO 4 m      | 20   | 2010 Mar 19   | Hale 5 m      | 12   |
| 2008 Jun 22   | MMT 6.5 m     | 4    | 2011 May 02   | Magellan 6.5 m| 8    |
| 2008 Jul 07   | Gemini South 8.1 m | 5 | 2013 Feb 06 | Gemini North 8.1 m | 42 |
| 2008 Aug 05   | CFHT 3.5 m    | 24   | 2013 Jul 05   | NOT 2.5 m     | 13   |
| 2008 Aug 30   | CFHT 3.5 m    | 52   | 2013 Aug 05   | Gemini North 8.1 m | 32 |

Note. All observations not part of the HiLat discovery survey are reported here. UT Date is the start of the observing run; Obs. is the number of astrometric measures reported from the observing run. Runs with low numbers of astrometric measures were either wiped out by poor weather or not meant for HiLat object follow-up originally.

This is the date of the first observation; targets were observed twice a month throughout the semester.

& Khushalani (2000) “orbit” code to the precision with which they are known. The typical fractional accuracies are on the order of a few 10^{-4}. As mentioned in P1, “in the cases of resonant objects even this precision may not be enough to precisely determine the amplitude of the resonant argument.” Actually, this may not even be enough to securely classify them as resonant. Thanks to our intensive tracking effort, dynamical classification is possible for 100% of the characterized sample.

4.1. Orbit Classification

We follow the dynamical classification scheme of Gladman et al. (2008), which was also used to determine the classification of the CFEPS sample. In this scheme, the Kuiper Belt is divided into three broad orbital classes based on orbital elements and dynamical behavior. We first check if the object is resonant (currently in MMR with Neptune or Uranus), then see if it is currently scattering (practically defined as a variation of semimajor axis of more than 1.5 au in a forward time integration over 10 Myr). If not, it is a classical or detached object: inner classical if semimajor axis is interior to the MMR 3:2 with Neptune, main classical if semimajor axis between the 3:2 and 2:1 MMR, outer classical if semimajor axis beyond the 2:1 MMR and e < 0.24, detached if semimajor axis beyond the 2:1 MMR and e > 0.24.

Even with our intensive tracking, 7 of our 21 characterized objects remain insecure, as defined in Gladman et al. (2008), due to their proximity to a (high-order) resonance (chaotic) border where the remaining astrometric uncertainty makes it unclear if the object is actually resonant. All characterized objects are listed in Table 3 according to their dynamical classification. The “insecure” objects are listed in the class corresponding to the majority of clones (Gladman et al. 2008) with the close-by resonance given in the comment column. None of these objects had archival observations before our discovery. The non-characterized objects (fainter than the 40% efficiency threshold) cannot be used in comparisons with the Survey Simulator. They are listed in Table 4 for completeness.

Assuming objects brighter than our limiting magnitude, our survey can detect objects as distant as R ∼ 125 au (R is the heliocentric distance in au), since the typical seeing was smaller than 0.9 arcsec, the time between first and third frame was 70–90 minutes, and the apparent motion at opposition is approximately θ′/hr ≈ (147 au)/R. Despite this sensitivity to large distances, the most distant object discovered in HiLat lies at 48.4 au from the Sun (HL7j4, an insecure resonant object in the 5:1 MMR with Neptune, Pike et al. 2015).

5. Results

CFEPS data presented in P1 were modeled independently for the inner, main, outer/detached classical, the scattering, and various resonant populations by P1 and Gladman et al. (2012). The model for the main classical belt is referred as the L7 model hereafter. According to P1, the cold component may very well exist only in the main classical belt. The hot component, on the contrary, permeates the whole belt, from the inner classical to the main classical to the outer/detached belt and all of the resonances. The cold component was well constrained by the ecliptic component of the survey.

HiLat was designed to have maximum sensitivity to high-inclination objects (Figure 2), and thus places strong constraints on the distribution of high-inclination objects, i.e., the hot population. The goal is thus to improve the L7 model.
5.1. Main Classical Belt and L7 Model

Our aim is to create a model that is compatible with both the CFEPS and HiLat detections. We are able to account for HiLat detections by slightly changing some parameters of the L7 orbital model, affecting only regions of phase space not well constrained by CFEPS detections. Here we concentrate on the model for the main classical belt, because this dynamical class alone constitutes nearly a third of the full HiLat sample. With the parameterization of L7 model, HiLat is sensitive almost exclusively to the hot component. Hence this is the part of the model that will be modified in the following. However, in what follows, we always run the full L7 model, including all components: kernel, stirred, and hot components.

5.1.1. Orbital Model

To estimate the quality of a model, we compare the survey detected sample to the sample returned by passing our intrinsic model through a survey simulator (see Jones et al. 2006 for details). Acceptance of a model is based on the Anderson–Darling statistic for each of $a$, $e$, $i$, $q$ (perihelion distance), $R$, and $r'$ and its level of significance $s$ (probability of the null hypothesis (the simulated and the observed samples are drawn from the same underlying distribution) being correct), determined using a bootstrap method (Press et al. 1992). $1 - s$ gives the rejectability of that hypothesis. As for CFEPS, we reject a model when the rejectability exceeds 95%. We determine the rejectability on the maximum of all six indicators we consider.

When creating the L7 model, P1 split the phase space into sub-regions (see Appendix of P1) to help separate the hot and cold components and account for the kernel and stirred components. HiLat detects almost exclusively the hot component, and the L7 model for the main classical belt retains the same level of significance ($\sim 20\%$) as with the previous survey simulator.

Using the improved survey simulator (see Bannister et al. 2016 for a description of the improvements) against the CFEPS detections, the L7 model for the main classical belt retains the same level of significance ($\sim 20\%$) as with the previous survey simulator.

To combine the CFEPS and HiLat sample we must make a color correction. CFEPS was run mostly with the $r'$ filter, except for 1 block with the $r$ filter and the pre-survey block with the $R$ filter. HiLat was run entirely with the $r'$ filter. The improved Survey Simulator correctly handles surveys observed in different filters, and accepts as input the colors of each
object. Here, for compatibility with previous works, we assume $g' - r' = 0.7$ and $g' - R = 0.8$ (this assumption agrees with more recent results from OSSOS, the Outer Solar System Origin Survey; Bannister et al. 2016).

When the biased L7 model is tested against the HiLat detections, the $i$ and $q$ distributions of the hot component are rejectable at >95%. An important feature of the L7 model for the main classical belt is the $q$ distribution of the hot component (see the Appendix of P1), which is essentially uniform between two limits, with rapid roll-over at both ends, with a width of 0.5 au. The upper limit is poorly constrained by CFEPS. To account for HiLat detections, we moved the upper roll-over of the hot-component $q$ distribution from 40 to 41 au, still with a width of 0.5 au. Because HiLat did not detect any main classical belt object with $q < 35$ au, we must impose a sharp cutoff on top of the $i$-dependent lower limit of the hot-component $q$ distribution. The new parameterization is described in the Appendix. Using this slight tuning of the L7 model continues to provide an acceptable match to the CFEPS detected sample, when considered independent of the HiLat sample. Extending the $q$ distribution of the L7 model somewhat allows compatibility with the HiLat $q$ distribution.

The $i$ distribution of the HiLat main classical belt detected sample is incompatible with the hot component of the L7 model. The CFEPS detected sample strongly rejects a hot population with a narrow inclination width because that model does not yield the correct ratio between low inclination and high inclination as compared to the detections in the CFEPS sample. The CFEPS sample rejects much larger inclination distributions ($\sigma \geq 30^\circ$; see Figure 4, dashed line) only because of the relative lack of low inclination objects in these distributions. The HiLat detected sample, on the contrary, rejects any model with too wide an inclination distribution because this survey is very sensitive to the high-inclination orbits. Even the inclination width $\sigma = 16^\circ$ preferred by CFEPS has a long tail containing too many objects with $i > 35^\circ$, which would have been detected by HiLat. But being completely insensitive to low-inclination orbits (HiLat cannot detect any of them), it can accept any values of $\sigma$ as long as they allow enough objects up to $i \simeq 35^\circ$. Thus HiLat is consistent with all values of $\sigma$ from $7^\circ.5$ to $15^\circ.5$ (Figure 4, dash-dotted line). Together, the two surveys combine high CFEPS sensitivity at low inclinations and HiLat’s improved sensitivity at high inclinations. The result is shown in Figure 4. Because our model rejection threshold is set at 5% significance, this analysis indicates that an acceptable value for each of CFEPS and HiLat separately and for their combination is an inclination width $\sigma$ in the range $14^\circ–15^\circ.5$, where all three curves exceed the threshold.

Separately, CFEPS and HiLat favor different values for the width and only marginally agree at the intersection (see Figure 4). There is tension between the models allowed by the two data sets. This raises doubts on the parameterization used here. Gulbis et al. (2010) introduced an inclination distribution given by $\sin(i)$ multiplied by a Gaussian of width $\sigma$, centered on a value $i_0$ greater than $0^\circ$ to fit what they called the Scattered population (Appendix). Pike et al. (2015) did the same to study the 5:1 MMR population. P1 mentioned the possibility to use a similar functional form to represent the Classical belt hot population inclination distribution, but concluded that the fit was good enough with the usual distribution and that the data did not demand the increased complexity of the extra parameter. Applying this functional form to the CFEPS, HiLat, and CFEPS+HiLat sample also does not improve the level of
significance enough to warrant the increased complexity of the extra parameter. So our preferred model retains the previous inclination distribution functional form, with a width $\sigma = 14^{+5}_{-5}$. We note, however, that the functional form here, while useful for discussion, is not a good description of the physical distribution of high-inclination TNOs.

Gulbis et al. (2010) also proposed the use of a Lorentzian for which they found a center ($14.1^{+1.2}_{-1.5}$) close to the one of the their Gaussian, but an essentially unconstrained width ($12.1^{+5.5}_{-100}$). Adams et al. (2014) re-analyzed a slightly expended sample from the same survey using the same Lorentzian functional form and found a higher inclination center ($21.99 \pm 0.77$) and a tight constrain on its width ($1.69 \pm 0.56$). Note, however, that the scattered population used in Gulbis et al. (2010) and Adams et al. (2014) is very different from our hot population, including only part of our hot population as well as our scattering population and other high-i objects.

### Table 5

| Population | CFEPS A | CFEPS B | HiLat A | HiLat B | CFEPS + HiLat A | CFEPS + HiLat B |
|------------|--------|--------|--------|--------|----------------|----------------|
| Hot        | 3, 700$^{+200}_{-700}$ | 3, 500$^{+500}_{-700}$ | 2, 100$^{+1400}_{-1300}$ | 2, 700$^{+1300}_{-1700}$ | 3, 500$^{+800}_{-800}$ | 3, 400$^{+600}_{-400}$ |
| Stirred    | 2, 700$^{+400}_{-550}$ | 2, 600$^{+550}_{-500}$ | 1, 550$^{+1400}_{-1300}$ | 2, 000$^{+200}_{-1300}$ | 2, 600$^{+200}_{-150}$ | 2, 500$^{+450}_{-450}$ |
| Kernel     | 800$^{+150}_{-150}$ | 750$^{+150}_{-150}$ | 450$^{+150}_{-150}$ | 400$^{+150}_{-150}$ | 800$^{+150}_{-150}$ | 750$^{+150}_{-150}$ |

Note: Our model estimates are given for each sub-population within the Kuiper Belt. The uncertainties reflect 95% confidence intervals for the model-dependent population estimate. Remember that the relative importance of each population will vary with the upper limit. The A columns correspond to a uniform color $g' - r' = 0.7$, while the B columns have $g' - r' = 0.45$ for the hot component and $g' - r' = 0.95$ for the cold component.

5.1.2. Population Estimates

Population estimates are dependent on the orbital model used to describe each TNO component, which we slightly modify from P1. They also depend on the correct modeling of the survey operation and detection efficiency. As explained in Bannister et al. (2016), the survey simulator has been improved to better represent the exact selection and rejection effects of objects based on measured magnitude rather than intrinsic magnitude. This has the potential of substantially affecting the population estimates due to the steep slopes of the absolute magnitude $H$ distributions.

We follow the same procedure as in Kavelaars et al. (2009), Gladman et al. (2012), and P1. We run our model, generating simulated objects, passing them through the survey simulator until we have detected the same number of objects in the simulation as in the real survey(s). We record this number and repeat the procedure 500 times. This gives us the distribution of likely population size. Table 5 columns A and B, give the population estimates, using our new model, to $H_g \leq 8.0$ to compare with P1. Compared to P1, we use the new q distribution and an i distribution with width $\sigma_i = 14^{+5}_{-5}$. Our CFEPS estimates are statistically indistinguishable from P1 estimates.

Although the various population estimates for a given component have overlapping error bars, HiLat estimates population sizes at just a little over half those of CFEPS. This is also reflected in the larger than observed fraction of objects detected from HiLat when running our model through the combined CFEPS+HiLat survey simulator; 12% of the simulated detections are from HiLat, while they represent only 6% of the real sample. This larger fraction from HiLat means the model plus survey simulator are more efficient at detecting objects in HiLat survey, hence needing a smaller underlying population to reach the required number of detections. This may be due to our choice of $g' - r'$ color for TNOs, a necessary parameter when combining surveys done in different band passes.

Up to now we used the $g' - r' = 0.7$ color derived from CFEPS sample for all components. However, the cold belt objects are redder than the hot ones (Dorosowandiram et al. 2002; Tegler et al. 2003). If the hot objects detected by HiLat are bluer than $g' - r' = 0.7$, then the number of objects brighter than $H_g = 8.0$ needed to match the real detections is larger. According to W.E. Fraser (2016, private communication), the cold component has a typical color $0.8 < g' - r' < 1.1$, while the hot component comprise mostly neutral objects with $0.4 < g' - r' < 0.7$, and a small fraction of objects as red as the cold component. Table 5, column B, gives the population estimates when using $g' - r' = 0.45$ for the hot component and $g' - r' = 0.95$ for the cold component. The three population estimates become more compatible with each other and the fraction of simulated detections from HiLat in CFEPS+HiLat simulations becomes 7%, similar to the real detected fraction. This result provides (unsurprising) evidence for the already known different $g' - r'$ colors of the various components, which must be accounted for when combining detections in different filters.

5.2. Other Populations

The HiLat characterized sample included six outer classical or detached objects, roughly half as many as were identified by CFEPS (P1 identified 13 non-scattering, non-resonant objects beyond 48 au). P1 established that the outer-detached population can be interpreted as a smooth extention beyond the 2:1 MMR of the hot main classical belt. We confirm this result with CFEPS+HiLat detection. We note, however, that the HiLat sample alone allows inclination widths $13^{\circ} < \sigma < 30^{\circ}$, possibly more excited than for the main classical belt. The combined CFEPS+HiLat sample allows an inclination width $12.5^{\circ} < \sigma < 20^{\circ}$. This is in agreement with the outer-detached population being a smooth extension of the hot classical population. We estimate the population beyond 48 au $N(H_g \leq 8.0) = 9500^{+4500}_{-3500}$ very similar to the P1 estimate.

After the main classical and the outer/detached objects, the single most represented population is the scattering objects. HiLat discovered four objects in this population, half as many as identified by CFEPS. Shankman et al. (2013) used the HiLat and CFEPS detections to study the absolute magnitude $H$ distribution of the scattering objects and showed that a divot in the $H$ distribution may be present. They also showed that a modified version of the orbital model of Kaib et al.
(2011a, 2011b) was a good fit to the orbital distribution of the scattering objects. Shankman et al. (2016) extended their work by including the detections from the first quarter of OSSOS (Bannister et al. 2016), confirming their previous results.

The HiLat characterized sample contains four resonant objects. One is in the 2:1 MMR and another in the 5:2 MMR with Neptune. These represent a small contribution to the known populations of these resonances from characterized surveys like CFPS, although the 3174 inclination of the 2:1 resonant orbit $\text{HL6r3}=2006\,\text{SG}_{1415}$ exceeds that of all other resonant TNOs, into the range of long-term instability (Li et al. 2014), meaning this object may not have resided in the 2:1 MMR for the age of the solar system, but rather be a more recent transiently stable capture from the scattering disk (Levison & Duncan 1997). HiLat made an important contribution to our understanding of the resonant population by discovering two objects in the 5:1 MMR (only one was known from CFPS), and another very close to the 5:1 MMR, $\text{HL8k1}=2008\,\text{JO}_{41}$ at 87.356 au; scientific interpretation of these discoveries have been reported in Pike et al. (2015).

5.3. Exotic Objects: 2008 $\text{KV}_{42}$ and (418993) 2009 $\text{MS}_{9}$

Among its 21 characterized detections, HiLat discovered two extraordinary TNOs. Both are scattering objects. The first one was discovered on 2008 May 31 in a field at moderate ecliptic latitude ($\sim30^\circ$). It is $\text{HL8m1}=2008\,\text{KV}_{42}$, the first known retrograde TNO. Although some people might classify this object as a Centaur, we use the Gladman et al. (2008) nomenclature and thus classify it as a scattering object. Although dynamical models can produce highly inclined and even retrograde objects with a $<30$ au, no published models produce objects with dynamics similar to 2008 $\text{KV}_{42}$. Details about this object and what it tells us about the origin and dynamical evolution of exotic scattering objects are developed in Gladman et al. (2009).

The second object is $\text{HL9m1}=(418993)\,2009\,\text{MS}_{9}$, discovered on the 2009 June 26 at a distance of 12.9 au from the Sun and an ecliptic latitude of $71^\circ$. It has a large ($a \approx 350$ au) and highly inclined ($i \approx 68^\circ$) orbit (Figure 5), which is also highly eccentric ($e \approx 0.968$). Inbound at 13 au at time of discovery, the pericenter of this extreme orbit was $\sim11$ au in 2013 February, so (418993) is transiting the range of heliocentric distances where comets have been observed to become active (Meech & Svorven 2004). (418993) thus may be the first observable object that has been in deep cold storage at hundreds of au for on the order of 5000 years. Under the hypothesis that this is a comet from a distant source (either the inner Oort Cloud, or something else as yet unknown), it is also quite possible that (418993) has never been interior to Saturn’s orbit (unlikely to be true for known Centaurs, which often have their perihelia altered as they interact with the giant planets).

A plausible scenario is that (418993) is a former Oort Cloud object that has had its orbit changed from nearly parabolic ($a > 1000$ au) to highly eccentric by an encounter with Saturn, Uranus, or Neptune. (418993) is currently only dynamically meta-stable on the order of $\sim10$ Myr, and may never have come inside the water-sublimation zone (heliocentric distances of 5–6 au). Many comet nuclei have been studied after the development of a coma, but only after the comets have left the inner solar system and are very dim (Lamy et al. 2004). MS9 had the advantages that, at time of discovery, it was bright ($r^\prime \sim 22$), inbound, and had no obscuring coma. Assuming an albedo $p = 0.04$ (common for comet nuclei, Lamy et al. 2004, but on the lower end for TNOs), this object has a radius $\sim20$ km. Not only is (418993) unique dynamically, but if it had become an active comet, it would have been the largest comet nucleus in recent times, after Hale–Bopp (C/1995 O1; radius = 37 km; Lamy et al. 2004).

At its discovery distance of 13 au, no coma has been detected in analysis of our deep 2009 August CFHT images, to a limit of 28 mag/arcsec$^2$. Other shorter-period comets have been observed to start cometary activity as far out as 12–14 au from the Sun (1P/Halley at 14 au and 2060 Chiron at 12 au; Meech & Svorven 2004). We observed (418993) at the Palomar 5 m in 2009 August and determined that it has a $\sim0.4$ mag light curve with a period of over either 6.5 (single peaked) or 13 hr (double peaked; Figure 6). Studying possible cometary activity on this object requires determining the rotational phase to remove this predictable brightness change. We obtained snapshot observations to monitor the cometary activity from 2010 August to 2011 February but detected none. From 2012 until the end of 2014, many observations of (418993) have been reported to MPC, around its perihelion passage, but none have reported detection of cometary activity.

6. Summary and Discussion

The HiLat survey was designed to address one of the shortcomings of CFPS, its lack of sensitivity to high-inclination objects. HiLat imaged about 700 sq. deg. from 12° to 85° ecliptic latitude. The survey was performed at CFHT in the r$^\prime$ filter and achieved limiting magnitudes ranging from $r^\prime = 22.4$ for the shallowest field to $r^\prime = 24.8$ for the deepest field. Being at high ecliptic latitude, the survey detected only 24 objects, of which 21 are brighter than the characterization limit. Thanks to the small number of objects and to our careful follow-up strategy, we tracked all characterized objects to precise orbit determination and orbital classification.

HiLat detected six objects from the hot main classical belt. We confirm the global parameterization of this component found by CFPS. An important finding of CFPS was that the $q$ distribution of the hot classical component is essentially flat between 35 and 40 au with poor constraint on this upper limit. The HiLat sample requires us to move the upper limit to 41 au.
Including the HiLat sample and survey in the analysis, we decrease slightly the width of the inclination distribution of the hot component to $\sigma = 14.5^\circ$.

The high sensitivity of HiLat survey to TNOs on highly inclined orbits permits formal rejection at high confidence of “wider” orbital $i$ distributions for the hot classical belt and, to a lesser extent, the detached components. The CFESPS survey already rejected “narrower” $i$ distributions. Having an $i$ distribution with little contribution below about $10^\circ$ and not extending much beyond $35^\circ$–$40^\circ$ is difficult to achieve with a broad Gaussian centered at $0^\circ$ distribution. It becomes increasingly clear that Equation (7) in Brown (2001) is not the appropriate representation for this distribution and something different should be considered. The distribution proposed by Gulbis et al. (2010) is an interesting possibility. A new $i$ distribution could have profound cosmogonic implications that would need to be investigated.

The exotic higher $i$ objects, like those found in HiLat (Figure 5), do not fit into this picture; we will call these $i \sim 90^\circ$ objects the “halo” component. Due to our sensitivity to high inclinations, these do not represent the tail of the $14.5^\circ$ Gaussian. Instead, these objects may point to a new source that feeds large-$i$ TNOs into the planetary system (Gladman et al. 2009). This may simultaneously be the source of the Halley-type comets (see Levison et al. 2006). Recently, Batygin & Brown (2016) pointed to (418993) as possible evidence that this source might be related to an undiscovered planet in the distant solar system ($a \sim 500$ au); producing $a < 50$ objects like 2008 KV$_{42}$ requires pulling objects from such a large-$a$ source down to such small semimajor axes and is exceedingly difficult due to the high encounter speeds with Neptune and Uranus (Gladman et al. 2009).

The OSSOS Survey (Bannister et al. 2016) will allow a careful consideration of the details of the $i$ distribution of the main hot component and the relative fraction of objects that must be in this halo population. The use of our characterized Hilat survey (coupled to CFESPS and OSSOS) permits powerful constraints to be placed on the $a/q$/$i$ distribution generated by any proposed model of where these extreme objects are coming from.

This work is based on observations obtained with MegaPrime/MegaCam, a joint project of CFHT and CEA/DAPNIA, at the Canada–France–Hawaii Telescope (CFHT), which is operated by the National Research Council (NRC) of Canada, the Institute National des Sciences de l’Univers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii. This research was supported by funding from the Natural Sciences and Engineering Research Council of Canada, the Canadian Foundation for Innovation, the National Research Council of Canada, and NASA Planetary Astronomy Program NNG04GI29G. This project could not have been a success without the dedicated staff of the Canada–France–Hawaii telescope as well as the assistance of the skilled telescope operators at KPNO and Mount Palomar. This work is based in part on data produced and hosted at the Canadian Astronomy Data Centre.

Facilities: CFHT (MegaPrime), WIYN, Hale, KPNO:2.1m, Blanco, MMT, Gemini:South, Subaru, Megellan:Clay, Gemini: Gillett (GMOS), NOT.

Appendix

We here detail the minor tuning to the L7 algorithm used to generate the hot population of the main classical belt, motivated by the HiLat sample’s greater sensitivity. The new algorithm becomes:

1. a perihelion distance $q$ distribution that is mostly uniform between 35 and 41 au, with soft shoulders at both ends extending over $\sim$1 au; the PDF is proportional to $1/(1 + \exp((35 - q)/(0.5))1 + \exp((q - 41)/(0.5)))$; any object with $q < 35$ au is rejected;
2. reject objects with $q < 38 - 0.2i$ (deg) to account for weaker long-term stability of low-$q$ orbits at low inclination.

The inclination distribution for the hot component remains $P(i) \propto \sin(i)\exp(-i^2/2\sigma^2)$, but with $\sigma = 14.5^\circ$.

References

Adams, E. R., Gulbis, A. A. S., Elliot, J. L., et al. 2014, AJ, 148, 55
Allen, R. L., Gladman, B., Kavelaars, J. J., et al. 2006, ApJL, 640, L83
Bannister, M. T., Kavelaars, J. J., Petit, J.-M., et al. 2016, AJ, 152, 70
Batygin, K., & Brown, M. E. 2016, AJ, 151, 22
Becker, A. C., Arraki, K., Kaib, N. A., et al. 2008, ApJL, 682, L53
Bernstein, G. M., & Khushalani, B. 2000, AJ, 120, 3323
Bernstein, G. M., Trilling, D. E., Allen, R. L., et al. 2004, AJ, 128, 1364
Brasser, R., Duncan, M. J., Levison, H. F., Schwamb, M. E., & Brown, M. E. 2012, Icar, 217, 1
Brown, M. E. 2001, AJ, 121, 2804
Brown, M. E., Trujillo, C. A., & Rabinowitz, D. L. 2005, ApJL, 635, L37
Buie, M. W., Millis, R. L., Wasserman, L. H., et al. 2003, EM&P, 92, 113
Doressoundiram, A., Peixinho, N., de Bergh, C., et al. 2002, AJ, 124, 2279
Fraser, W. C., & Brown, M. E. 2012, ApJ, 749, 33
