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The Canada-France Ecliptic Plane Survey (CFEPS) - High Latitude Component

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ABSTRACT

We report the orbital distribution of the Trans-Neptunian objects (TNOs) discovered during the High Ecliptic Latitude (HiLat) extension of the Canada-France Ecliptic Plane Survey (CFEPS), conducted from June 2006 to July 2009. The HiLat component was designed to address one of the shortcomings of ecliptic surveys (like CFEPS), their lack of sensitivity to high-inclination objects. We searched 701 deg² of sky ranging from 12° to 85° ecliptic latitude and discovered 24 TNOs, with inclinations between 15° to 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 (2001), the HiLat sample combined with CFEPS imposes a width $14^\circ \leq \sigma \leq 15.5^\circ$, with a best match for $\sigma = 14.5^\circ$. HiLat discovered the first retrograde TNO, 2008 KV₄₂, with an almost polar orbit with inclination 104°, and (418993), a scattering object with perihelion in the region of Saturn's influence, with $a \sim 400$ AU and $i = 68^\circ$.

Subject headings: Kuiper Belt, surveys

1. Introduction

The Kuiper Belt is widely thought of as a left-over flattened disk of planetesimals extending from ~ 30 to a thousand AU from the Sun. Several Kuiper Belt surveys broke ground by investigating the gross

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10 properties of the TNO diameter and orbital distributions via large samples (Jewitt et al. 1996; Gladman et al.
 11 2001; Millis et al. 2002; Trujillo et al. 2001). It is now obvious that this region must have been heavily
 12 perturbed late in the process of giant planet formation. The Kuiper Belt’s small mass and the existence of
 13 many objects with large orbital inclinations (i up to 50°) indicate that a process either emptied most of the
 14 mass out of the primordial Kuiper Belt or, more dramatically, that the Kuiper Belt was transported to its
 15 current location during planetary migration. Recent models suggest stellar encounters (e.g., Levison et al.
 16 (2010); Brassier et al. (2012)) or the existence of a 9th planet (Batygin & Brown 2016) may play an important
 17 role in shaping the outer solar system.

18 The dynamical structure of the Kuiper Belt is much more complex than anticipated by the commu-
 19 nity. Surveys with known high-precision detection efficiencies and which track essentially all their ob-
 20 jects, to avoid ephemeris bias (Kavelaars et al. 2008; Jones et al. 2010), are needed to disentangle these
 21 details and the cosmogonic information they provide. The Canada-France ecliptic plane survey (CFEPS)¹
 22 (Jones et al. 2006; Kavelaars et al. 2009; Petit et al. 2011, P1 hereafter), was a fully characterized² survey
 23 that tracked more than 80% of its discoveries to orbit classification³. Although discovering and tracking
 24 only 169 TNOs, this survey produced solid science contributions to Kuiper Belt science (P1; Jones et al.
 25 2006; Kavelaars et al. 2009; Gladman et al. 2012). Without this accurate calibration and extensive tracking,
 26 it is risky to perform quantitative interpretation of the orbital distribution of the 800 multi-opposition TNOs
 27 in MPC database with unknown detection and tracking biases (Jones et al. 2010).

28 The inclination distribution of the ‘main’ Kuiper Belt is now recognized as bimodal (Brown 2001;
 29 Kavelaars et al. 2008), with a ‘cold’ component of objects with inclination width around 3° and a ‘hot’
 30 component with a very broad inclination distribution, much like the disk/halo structure of the galaxy. This
 31 discovery came at the same time as the realization that the cold component appears to have a different colour
 32 distribution than the hot component (Doressoundiram et al. 2002; Tegler et al. 2003; Fraser & Brown 2012;
 33 Peixinho et al. 2015). The orbital distribution of these high-inclination objects has a huge lever arm on mod-
 34 els of outer Solar System formation and evolution, which include ideas like passing stars (Ida et al. 2000;
 35 Kenyon & Bromley 2004; Morbidelli & Levison 2004; Kaib et al. 2011) that predict mean inclinations in-
 36 creasing with semimajor axis, rogue planets (Gladman & Chan 2006) that predict inclination decreasing
 37 with semimajor axis or transplanting almost all TNOs to their current locations during a large-scale reorga-
 38 nization of the planetary system (Thommes et al. 1999; Levison et al. 2008; Nesvorný 2015).

39 For both components the distribution of orbital inclination can be modelled as $P(i) \propto \sin(i) \exp(-i^2/2\sigma^2)$
 40 (Brown 2001). The distribution of the hot component appears to have a Gaussian width σ of at least
 41 15° (P1; Brown 2001; Kavelaars et al. 2009; Gulbis et al. 2010), but constraining the largest inclinations
 42 is difficult because detection biases in ecliptic surveys strongly disfavour their discovery. About two dozen

¹<http://www.cfeps.net>

²A survey is characterized when all detection circumstances are known: telescope pointings, efficiency of detection w.r.t. mag-
 nitude and apparent motion, ..., so that one can simulate the survey. It is fully characterized if tracking has no orbital bias. An object
 is characterized when its detection efficiency is large enough that it is accurately determined (Petit et al. 2004)

³Assigning an orbit to a dynamical class, as defined by Gladman et al. (2008)

43 TNOs with orbital inclinations in excess of 40° are now known. Eris, the belt’s most massive known mem-
 44 ber (Brown et al. 2005), is in this group along with 2004 XR₁₉₀ (discovered by our group during CFEPS;
 45 Allen et al. 2006), the lowest- e orbit known TNO with semi-major axis beyond 50AU.

46 Kuiper Belt objects with large inclinations spend the majority of their time at high ecliptic latitudes
 47 (Fig. 1) and are poorly represented in the ecliptic surveys (including the main component of CFEPS). Even
 48 more dramatically, it has become clear that the size distribution of the high inclination component is flatter
 49 (number of objects increases slower when size decreases) than the ecliptic component (P1; Levison & Stern
 50 2001; Bernstein et al. 2004; Fraser et al. 2014). So deeper surveys concentrating on the ecliptic will be
 51 increasingly dominated by low inclination objects.

52 The situation at the end of 2006 was that a large fraction of the sky within a few degrees of the ecliptic
 53 had been covered by a few large surveys, with magnitude limits in the range of $m_R=20-23$. Being insensitive
 54 to high inclination objects (Fig. 2), ecliptic surveys have poor sensitivity to the width of the hot population.
 55 Thanks to two deep blocks of 11 deg^2 (one at 10° and another at 20° ecliptic latitude) the CFEPS efficiency
 56 decreases less than most other ecliptic surveys towards higher ecliptic latitudes. Still, although CFEPS
 57 prefers a hot population inclination width σ of 16° , it could not reject a width of 25° . Actually what
 58 limits the value of σ is the relative decrease of the number of low and intermediate inclination objects when
 59 increasing σ . Using the converted Palomar Schmidt, Trujillo & Brown (2003) had examined the majority of
 60 the northern sky to a depth of $m_R \sim 20.5$ (limit for median observing conditions), discovering several of
 61 the largest known objects; several of these large-inclination objects (like Eris) were close to the depth and
 62 motion limits of that survey due to their great distances. The ESSENCE Supernova Survey (Becker et al.
 63 2008) announced the detection of 14 TNOs found in images covering $\sim 11 \text{ deg}^2$ to $r' \sim 23.7$ in the ecliptic
 64 latitude range -21° to 5° ; this work also showed that once outside of the ecliptic core, the sky density
 65 is consistent with even a uniform distribution in latitude. Such a distribution would not be rejected by any
 66 characterized surveys known at the time. We decided to perform a deep survey to magnitude $m_R \sim 23.5-$
 67 24.0 at high ($> 15^\circ$) ecliptic latitudes, called HiLat, to probe the hot component of the Kuiper Belt at sizes
 68 smaller than achieved by the Palomar wide area survey (Trujillo & Brown 2003) and SDSS. Although HiLat
 69 is insensitive to objects with inclinations below 10° ecliptic latitude (Fig. 2), it complements existing surveys
 70 because its design makes it very sensitive to objects having inclinations beyond $20^\circ-30^\circ$ (Fig. 2).

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

- 74 1. A list of detected HiLat TNOs, associated with the sky location of discovery,
- 75 2. a characterization of each survey discovery observation (detection efficiency as a function of magni-
 76 tude, motin on sky; rate range searched; pointing of observations; etc.),
- 77 3. a Survey Simulator that takes a proposed Kuiper Belt model, exposes it to the known detection biases
 78 of the HiLat blocks and produces simulated detections to be compared with the real detections, and
- 79 4. the updated CFEPS model populations accounting for the HiLat detections.

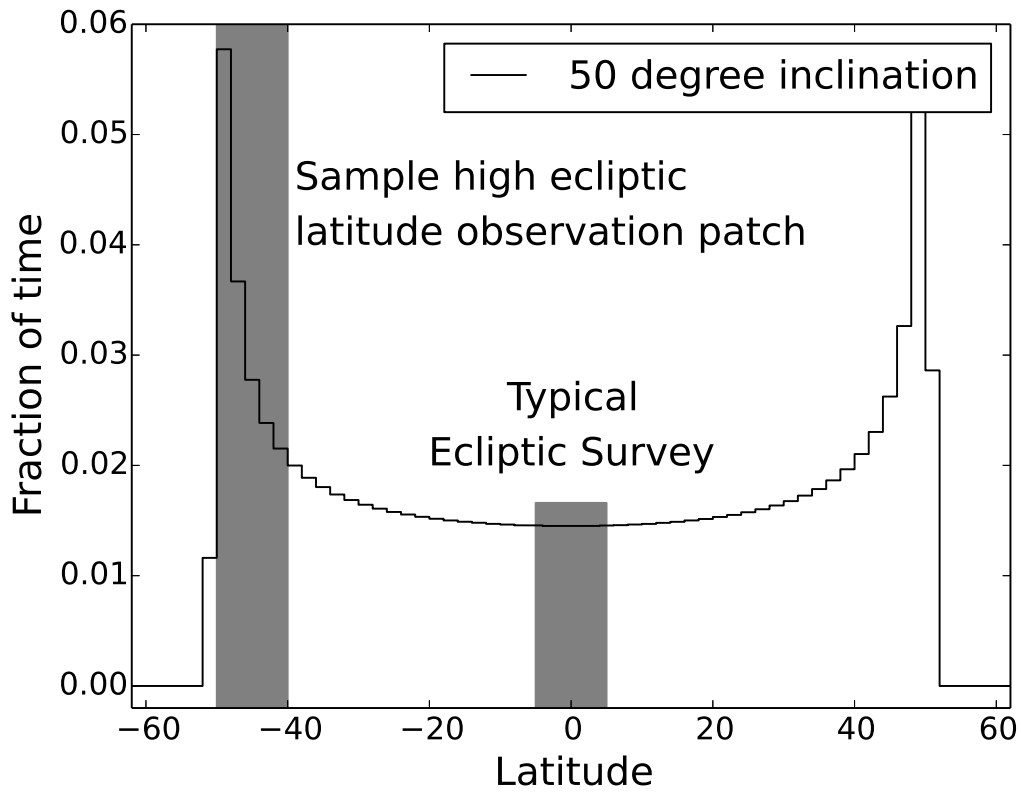


Fig. 1.— Fraction of time spent at each ecliptic latitude for a sample object with an orbital inclination of 50 degrees. Previous surveys have mostly concentrated on low ecliptic latitudes where their sensitivity to high inclinations objects is comparatively low (central grey region). A survey concentrating on the area between 40–50° latitude (like parts of HiLat, see Table 1 and Fig. 3, left grey region), where high inclination objects spend much of their orbital period, would be more sensitive to these objects.

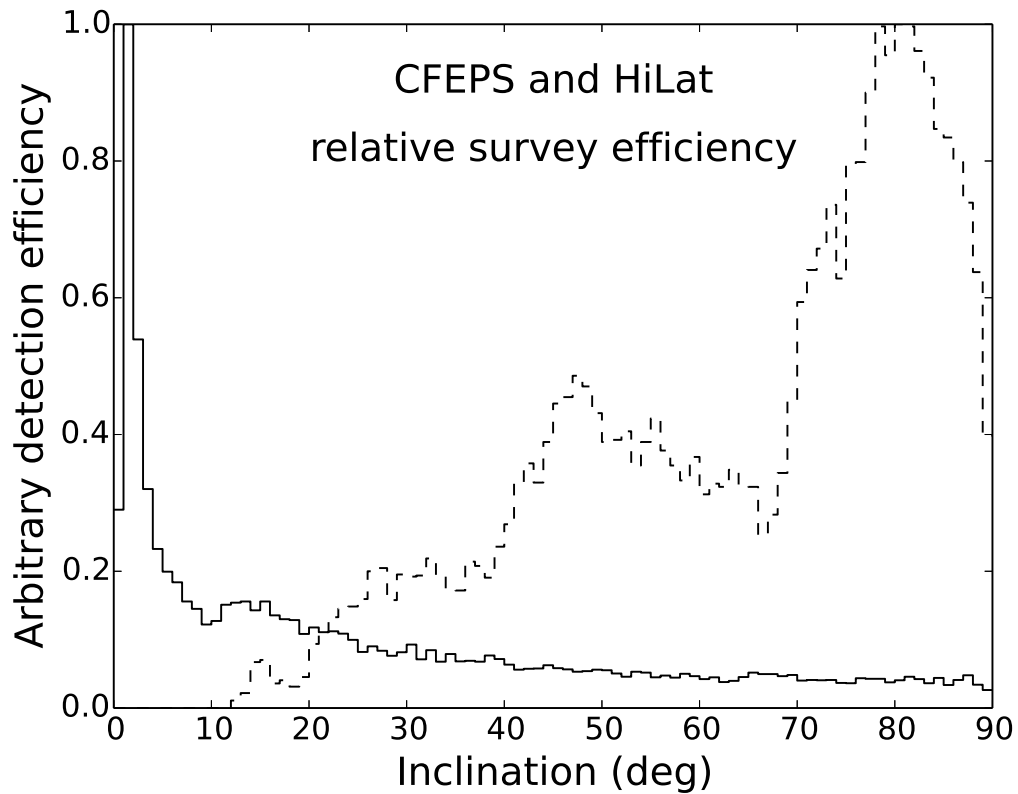


Fig. 2.— An illustration of the contrasting detection efficiencies of CFEPS (solid line) and HiLat (dashed line) as a function of ecliptic inclination, given their actual pointing histories. The orbital distribution model used here is the one derived from CFEPS, except for the inclination which was drawn uniformly between 0–90°. The scaling of each histogram is arbitrary, what matters here is the relative efficiency of a given survey to different inclinations.

2. Observations and Initial Reductions

80

81 The discovery component of the HiLat project imaged ~ 700 square degrees of sky, all of which was
82 at ecliptic latitude larger than 12° , extending almost to the North ecliptic pole (85° , Fig. 3). Discovery
83 observations, comprising a triplet of images 1 hour apart each on the date listed in Table 1, and a *nailing*
84 observation, a single image acquired a few nights away from the discovery triplet, were all acquired using
85 the Canada-France-Hawaii Telescope (CFHT) MegaPrime camera which delivered discovery image quality
86 (FWHM) of 0.7–0.9 arc-seconds in queue-mode operations. The observations occurred in *blocks* of 11 to
87 32 contiguous fields, cycling three times between the fields. The number of fields observed in a series was
88 chosen such as to have ~ 1 hour between two consecutive observations of the same field. When a block was
89 too large to be observed within one night, it was split into two sub-blocks observed during close-by nights,
90 with similar observing conditions. All discovery imaging data is publicly available from the Canadian
91 Astronomy Data Centre (CADC⁴).

92 The HiLat designation of a block was: a leading ‘HL’ followed by the year of observations (6 to
93 9) and then a letter representing the two week period of the year in which the search observations were
94 acquired (example: HL7j occurred in the second half of May 2007), similar to CFEPS naming scheme.
95 Discovery observations occurred between June 2006 and June 2008 for the coverage below 60° ecliptic
96 latitude, followed by observations between 60° and 85° ecliptic latitude from May to July 2009. This last
97 part of the survey is simply named HL9 as it was acquired as 22 contiguous blocks over this time span.

98 The discovery fields were chosen in order to maximize our sensitivity to the latitude distribution of the
99 Kuiper Belt, in particular the high inclination TNOs. Observing at high ecliptic latitude ensured that we
100 observed only high-inclination TNOs, and greatly decreased the pressure for follow-up observations, as the
101 number of TNOs per unit area drops sharply away from the ecliptic. The ecliptic longitudes were chosen
102 to avoid the galactic plane, and maximize our chances to get discovery and tracking observations (due to
103 typical weather at time of opposition for the discovery field, observing request pressure on the telescope).
104 Each of the discovery blocks was searched for TNOs using our Moving Object Pipeline (MOP; see Petit et al.
105 2004). Table 1 provides a summary of the survey fields, imaging circumstances and detection thresholds.
106 Subsequent tracking, over the next 2 or more oppositions, occurred at a variety of facilities, including CFHT,
107 summarized in Table 2. The field sequencing and follow-up strategy of this survey are similar to those of
108 CFEPS (Allen et al. 2006; Kavelaars et al. 2009; Petit et al. 2011). Our discovery and tracking observations
109 were made using short exposures designed to maximize the efficiency of detection and tracking of the TNOs
110 in the field. These observations do not provide the high-precision flux measurements necessary for possible
111 taxonomic classification based on broadband colours of TNOs and we do not comment here on this aspect
112 of the HiLat sample.

⁴<http://www.cadc.hia.nrc.gc.ca>

Table 1. Summary of Field positions and Detections.

Block	RA HRS	Dec deg	Area deg ²	Fill Factor	Detections		Ecl. lat. range (deg)	Discovery		limit r_{AB}	Detection limits	
					D	T		date	filter		rate (“/h)	direction (deg)
HL6l	18:16	-06:49	15	0.80	0	0	11:50–20:50	2006-06-23	r.MP9601	22.37	0.5 to 6.1	-17.8 to 16.4
HL6r	22:37	+07:04	16	0.80	7	6	12:20–16:40	2006-09-18	r.MP9601	23.89	0.5 to 6.1	-43.6 to -8.2
HL7a	13:06	+55:00	32	0.90	0	0	49:40–60:00	2007-03-18	r.MP9601	23.58	0.5 to 5.7	6.6 to 47.8
HL7b	11:33	+37:30	32	0.88	0	0	27:00–35:40	2007-03-23	r.MP9601	22.89	0.5 to 5.4	-10.0 to 33.8
HL7c	11:33	+29:30	32	0.89	4	4	19:50–28:40	2007-03-21	r.MP9601	23.72	0.5 to 5.8	-3.1 to 36.3
HL7d	12:49	+57:00	32	0.84	0	0	49:30–59:50	2007-04-09	r.MP9601	23.28	0.5 to 4.6	-25.7 to 26.9
HL7e	13:23	+52:58	32	0.87	0	0	49:40–60:10	2007-04-22	r.MP9601	23.47	0.5 to 4.7	-25.2 to 27.0
HL7j	16:22	+12:53	32	0.90	5	5	22:50–40:20	2007-06-12	r.MP9601	23.49	0.5 to 5.6	-22.0 to 19.8
HL7l	17:47	+18:03	27	0.90	0	0	37:50–45:00	2007-06-12	r.MP9601	23.35	0.5 to 6.2	-10.1 to 22.1
HL7o	22:12	+22:02	32	0.90	0	0	20:30–39:40	2007-08-20	r.MP9601	22.74	0.5 to 6.3	-28.0 to 1.2
HL7p	22:06	+19:23	32	0.84	4	4	19:40–39:10	2007-09-06	r.MP9601	23.85	0.5 to 6.2	-41.3 to -7.3
HL7s	23:59	+27:54	31	0.98	0	0	19:30–37:00	2007-09-19	r.MP9601	23.38	0.5 to 6.3	-35.3 to -3.9
HL8a	09:24	+63:30	30	0.90	1	1	40:00–50:20	2008-01-08	r.MP9601	23.76	0.6 to 6.6	22.1 to 50.1
HL8b	09:52	+61:60	25	0.90	0	0	40:30–49:50	2008-01-09	r.MP9601	23.24	0.6 to 6.6	26.0 to 54.0
HL8h	16:32	+09:58	11	0.88	0	0	29:10–35:50	2008-05-05	r.MP9601	23.91	0.5 to 6.2	5.4 to 35.8
HL8i	16:21	+25:33	11	0.90	0	0	44:40–47:30	2008-05-09	r.MP9601	24.31	0.5 to 6.3	8.1 to 37.5
HL8k	17:35	+24:25	12	0.90	1	1	44:50–49:50	2008-05-11	r.MP9601	24.63	0.5 to 6.4	16.4 to 41.0
HL8l	17:36	+19:15	13	0.90	0	0	39:40–45:50	2008-05-13	r.MP9601	24.15	0.5 to 6.3	13.0 to 38.8
HL8m	16:58	+23:15	12	0.90	0	0	39:50–49:50	2008-05-30	r.MP9601	24.26	0.5 to 6.1	-7.9 to 26.1
HL8n	16:53	+22:33	11	0.89	1	1	39:40–50:30	2008-05-31	r.MP9601	24.80	0.5 to 6.1	-9.1 to 25.5
HL8o	16:48	+23:00	12	0.90	0	0	39:30–50:20	2008-06-07	r.MP9601	24.26	0.5 to 5.8	-17.7 to 21.1
HL9	18:45	+55:08	219	0.92	1	1	59:30–85:20	2009-06-16	r.MP9601	24.28	0.5 to 20.0	-20.0 to 90.0
Grand Total			701		24	21						

Note. — RA/Dec is the approximate center of the field. Fill Factor is the fraction of the rectangle Area covered by the mosaic and useful for TNO searching. D is the number of TNOs detected in the block, T is the number of them that have been tracked to dynamical classification. Only one HL6r detection with apparent magnitude beyond the characterization limit, was not tracked to a high-quality orbit. The limiting magnitude of the survey, r_{AB} , is in the SDSS photometric system and corresponding to a 40% efficiency of detection. Detection limits give the limits on the sky motion in rate (“/hr) and direction (“zero degrees” is due West, and positive to the North).

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

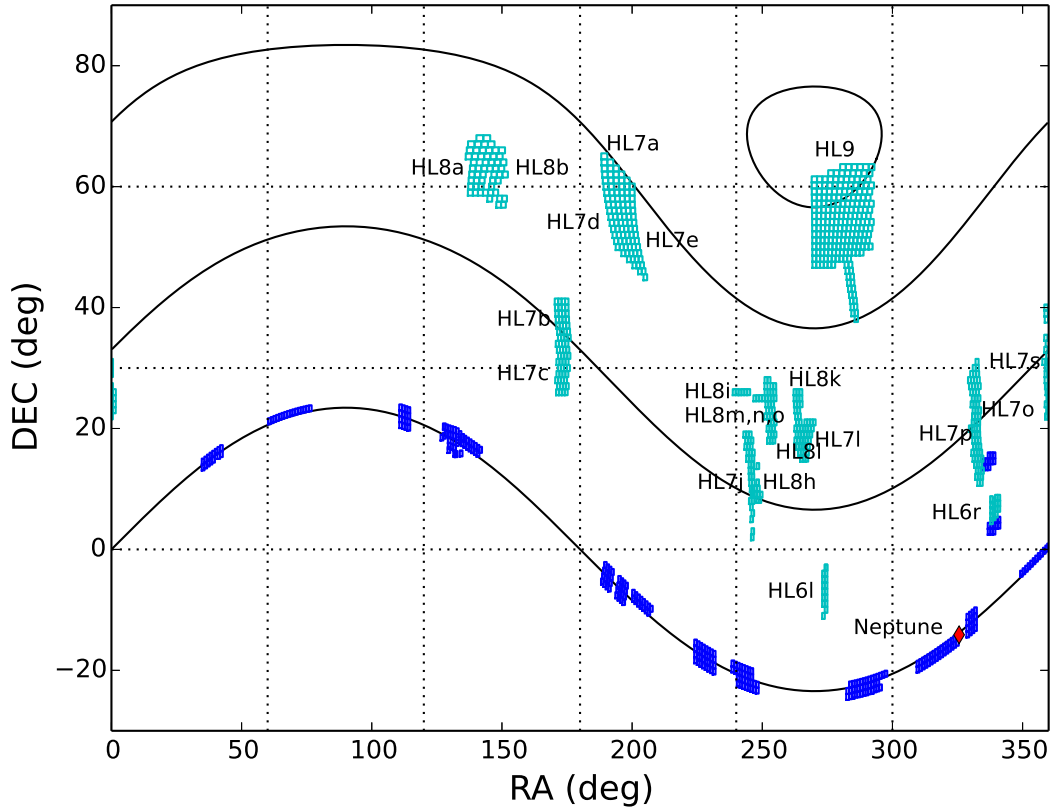


Fig. 3.— Geometry of the HiLat discovery-blocks. The RA and Dec grid is indicated with dotted lines. The solid curves show constant ecliptic latitudes of 0° , 30° , 60° , 80° , from bottom to top. The blue rectangles mostly along the ecliptic indicate CFEPS pointings, the cyan rectangles indicate the HiLat survey pointings. The red diamond indicates the position of Neptune on 2016-07-31.

3. Sample Characterization

113

114 As is now the norm (Trujillo & Jewitt 1998; Jewitt et al. 1998; Gladman et al. 1998; Trujillo et al.
 115 2000; Gladman et al. 2001; Petit et al. 2006; Kavelaars et al. 2009; Petit et al. 2011), we characterized the
 116 magnitude-dependent detection probability of each discovery block by inserting artificial sources in the im-
 117 ages. We performed differential aperture photometry for each of our detected objects observed on photomet-
 118 ric nights. Our photometry is reported in the Sloan system (Fukugita et al. 1996) with the calibrations con-
 119 tained in the header of each image as provided by the ELIXIR processing software (Magnier & Cuillandre
 120 2004). It can be found in Tables 3 and 4. All HiLat discovery observations that detected TNOs were acquired
 121 in photometric conditions in a relatively narrow range of seeing conditions due to queue-mode acquisition.

122 Those real objects in each block that have a magnitude brighter than that block’s 40% detection prob-
 123 ability are considered to be part of the HiLat *characterized sample*. Because detection efficiencies below
 124 $\sim 40\%$ determined by human operators and our software diverge (Petit et al. 2004), and since characteriza-
 125 tion is critical to our goals, we are unable to utilize the sample faint-ward of the measured 40% detection
 126 efficiency level for quantitative analysis (although we report these discoveries, the majority of which were
 127 tracked to precise orbits). The *characterized* HiLat sample consists of 21 objects of the 24 discovered
 128 (Table 3). The magnitude distribution of objects detected brighter than our cutoff is consistent with the
 129 shape of the TNO luminosity function (Petit et al. 2008) and the typical decay in detection efficiency due to
 130 gradually increasing stellar confusion and the rapid fall-off at the SNR limit.

131

4. Tracking

132 For typical (i.e., low ecliptic latitude) surveys to depth $r' \sim 23.5\text{--}24$, the observing load of tracking
 133 observations to secure the objects and determine their orbits represents many times the time spent for discov-
 134 ery. In such a case, a ~ 700 square degree survey with fully tracked objects would be prohibitive. However,
 135 because HiLat covers very high ecliptic latitudes, the number of object per square degree at our limiting
 136 magnitude goes down dramatically beyond $30\text{--}35^\circ$ and we detected only 24 objects (21 characterized).
 137 Hence the tracking observing load was much lower than for an ecliptic survey and

138 All of the 21 characterized and 2 of the 3 non-characterized objects were followed for at least 3 op-
 139 positions. Objects that still had uncertain dynamical classifications were then followed up to 7 oppositions,
 140 mostly for resonant or near-resonant objects. The global release of the complete observing record for all
 141 HiLat objects is available from the MPC (Petit et al. 2015) and the entire astrometric data for the HiLat
 142 objects can be found on the Besançon TNO database⁵. The correspondence between HiLat internal designa-
 143 tions and MPC designations can be determined using Tables 3 and 4 or from the Besançon TNO database.
 144 All characterized and tracked objects are prefixed by *HL* and are used with the survey simulator for our
 145 modelling below.

⁵<http://modb.obs-besancon.fr/>

Table 3. Characterized Object Classification.

DESIGNATIONS		a	e	i	R	m_r	σ_r	H_r	Comment
CFEPS	MPC	(AU)		($^\circ$)	(AU)				
Resonant Objects									
HL6r3	2006 SG415	47.931(6)	0.2915(1)	31.376(0)	35.009	23.27	0.03	7.75	2:1
HL7j3	2007 LG38	55.45(2)	0.4340(3)	32.579(0)	32.219	22.93	0.09	7.68	5:2
HL7c1	2007 FN51	87.49(3)	0.6188(2)	23.237(0)	39.100	23.20	0.06	7.17	5:1 I
HL7j4	2007 LF38	87.57(3)	0.5552(2)	35.825(0)	48.432	22.53	0.09	5.54	5:1 I
Inner Classical Belt									
HL7p1	2007 RY326	38.817(9)	0.06776(9)	25.479(0)	37.952	23.20	0.12	7.30	
Main Classical Belt									
HL6r1	2007 RL314	40.386(8)	0.0386(4)	21.057(1)	40.771	22.97	0.07	6.79	
HL6r5	2006 SE415	42.599(8)	0.027(1)	18.517(1)	42.266	23.73	0.12	7.40	
HL6r6	2006 SF415	43.20(2)	0.077(1)	15.712(0)	40.713	23.87	0.09	7.70	
HL7c2	2007 FM51	45.53(1)	0.159(1)	29.221(1)	42.561	23.00	0.15	6.59	
HL7p2	2007 RW326	45.92(1)	0.2355(2)	20.500(0)	35.127	23.70	0.10	8.16	I (17:9)
HL7p3	2007 RX326	46.096(7)	0.1565(3)	25.029(0)	39.343	23.30	0.30	7.25	
Detached/Outer Classical Belt									
HL6r2	2006 SH415	49.759(9)	0.2539(3)	25.048(0)	38.189	23.60	0.06	7.71	
HL7c3	2007 FO51	50.37(3)	0.2873(6)	27.946(0)	37.560	22.87	0.19	6.99	I (13:6)
HL7j5	2007 LE38	54.05(1)	0.2267(1)	35.966(1)	41.800	23.27	0.07	6.93	
HL6r4	2007 RM314	70.81(2)	0.4846(2)	20.884(0)	42.622	22.70	0.17	6.33	I (18:5)
HL7j1	2007 LJ38	72.37(3)	0.4698(3)	31.540(0)	38.848	23.07	0.19	7.03	I (15:4)
HL8k1	2008 JO41	87.35(2)	0.5431(1)	48.815(0)	44.453	24.57	0.12	7.91	
Scattering Disk									
HL8a1	2008 AU138	32.392(3)	0.3745(2)	42.826(1)	44.518	22.93	0.23	6.29	
HL8n1	2008 KV42	41.532(4)	0.49138(7)	103.447(0)	31.849	23.73	0.03	8.52	
HL7j2	2007 LH38	133.93(4)	0.72523(8)	34.197(0)	37.376	23.37	0.03	7.50	I (19:2)
HL9m1	2009 MS9	348.9(2)	0.96847(1)	68.016(0)	12.872	21.13	0.09	9.57	

Note. — a : semimajor-axis (AU); e : eccentricity; i : inclination (degrees); R : distance to the Sun at discovery time (AU); m_r : apparent magnitude of the object in MegaPrime r' filter; σ_r : uncertainty on the magnitude in that filter; H_r is the absolute magnitude in r band, given the distance at discovery; In Comment column, M:N: object in the M:N resonance; I: indicates that the orbit classification is insecure (see Gladman et al. (2008) for an explanation of the exact meaning); (M:N): the insecure object may be in the M:N resonance. For the orbital elements the number in “()” gives the uncertainty on the last digit.

Table 4. Non Characterized Object Classification.

DESIGNATIONS		a	e	i	R	m_r	σ_r	H_r	Comment
CFEPS	MPC	AU		$^\circ$	AU				
Resonant Objects									
uHL7c4	2007 FP51	44.760(6)	0.2017(1)	25.606(0)	36.688	23.80	0.20	8.02	20:11 I
Detached Classical Belt									
uHL7p4	2007 RZ326	52.676(8)	0.3465(1)	37.268(0)	38.300	23.93	0.09	7.98	
Non classified objects									
uHL6r7	2006 SN415	—	—	—	38(7)	24.50	0.25	8.65	

Note. — Same as Table 3 for non characterized objects.

146 The tracking observations provide sufficient information to allow reliable orbits to be determined such
147 that unambiguous dynamical classification can be achieved in the majority of cases. Orbital elements are
148 computed using the Bernstein & Khushalani (2000) ‘orbfit’ code. Ephemerides errors for the coming year
149 are as small as a few tenths of an arcsecond for several objects, others have uncertainties up to of order
150 10 arcseconds. Our protocol was to pursue tracking observations until the semimajor axis uncertainty was
151 $< 0.1\%$; in Tables 3 and 4, orbital elements are shown to the precision with which they are known, with
152 typical fractional accuracies on the order of a few 10^{-4} . In the cases of resonant objects even this precision
153 may not be enough to precisely determine the amplitude of the resonant argument, or even securely classify
154 them as resonant. Thanks to our intensive tracking effort, dynamical classification is possible for 100% of
155 the characterized sample.

156

4.1. Orbit classification

157

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

165

Using this classification procedure, 7 of our 21 characterized objects remain insecure, as defined in
166 Gladman et al. (2008), due to their proximity to a (high-order) resonance border where the remaining astro-
167 metric uncertainty makes it unclear if the object is actually resonant. We list these “insecure” objects in the
168 category shown by the majority of the clones (Gladman et al. 2008) and give the nearby resonance in the
169 comment column. Table 3 gives the classification of all characterized objects. None of these objects had
170 archival observations before our discovery. Table 4 gives the classification of the tracked objects below the
171 40% detection efficiency threshold, hence deemed un-characterized and not used in our Survey Simulator
172 comparisons.

173

The apparent motion of TNOs in our opposition discovery fields is approximately $\theta('/\text{hr}) \simeq (147 \text{ AU})/R$,
174 where R is the heliocentric distance in AU. With a typical seeing of 0.7–0.9 arcsecond and a time base of
175 70–90 minutes between first and third frames, we were sensitive to objects as distant as $R \simeq 125 \text{ AU}$, pro-
176 vided they are brighter than our magnitude limit. Despite this sensitivity to large distances, the most distant
177 object discovered in HiLat lies at 48.4 AU from the Sun (HL7j4, an insecure resonant object in the 5:1 MMR
178 with Neptune (Pike et al. 2015)).

179

5. Results

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

186 HiLat was designed to have maximum sensitivity to high-inclination objects (Fig. 2), and thus places
187 strong constraints on the distribution of high-inclination objects, i.e., the hot population. The goal is thus to
188 improve the L7 model.

189

5.1. Main Classical belt and L7 model

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

197

5.1.1. Orbital model

198 To estimate the quality of a model, we compare the survey detected sample to the sample returned by
199 passing our intrinsic model through a survey simulator (see Jones et al. 2006, for details). Acceptance of a
200 model is based on the Anderson-Darling statistic for each of a , e , i , q [perihelion distance], R and r' and its
201 level of significance s (probability of the null hypothesis [the simulated and the observed samples are drawn
202 from the same underlying distribution] being correct), determined using a bootstrap method (Press et al.
203 1992). $1 - s$ gives the rejectability of that hypothesis. As for CFEPS, we reject a model when the rejectability
204 exceeds 95%. We determine the rejectability on the maximum of all 6 indicators we consider. When creating
205 the L7 model, P1 split the phase space into sub-regions (see Appendix A of P1) to help separate the hot and
206 cold components and account for the kernel and stirred components. HiLat detects almost exclusively the
207 hot component, and the sample size is small, thus we determine the significance examining the full orbital
208 phase space occupied by the main-belt.

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

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

218 When the biased L7 model is tested against the HiLat detections, the i and q distributions of the hot
 219 component are rejectable at $> 95\%$. An important feature of the L7 model for the main classical belt is the q
 220 distribution of the hot component (see Appendix A of P1), which is essentially uniform between two limits,
 221 with rapid roll-over at both ends, with a width of 0.5 AU. The upper limit is poorly constrained by CFEPS.
 222 To account for HiLat detections, we moved the upper roll-over of the hot-component q distribution from 40
 223 to 41 AU, still with a width of 0.5 AU. Because HiLat did not detect any main classical belt object with
 224 $q < 35$ AU, we must impose a sharp cut-off on top of the i -dependent lower-limit of the hot-component q
 225 distribution. The new parameterization is described in Appendix A. Using this slight tuning of the L7 model
 226 continues to provide an acceptable match to the CFEPS detected sample, when considered independent of
 227 the HiLat sample. Extending the q -distribution of the L7 model somewhat allows compatibility with the
 228 HiLat q -distribution.

229 The i -distribution of the HiLat main classical belt detected sample is incompatible with the hot compo-
 230 nent of the L7 model. The CFEPS detected sample strongly rejects a hot population with a narrow inclination
 231 width because that model does not yield the correct ratio between low inclination and high inclination as
 232 compared to the detections in the CFEPS sample. The CFEPS sample rejects much larger inclination distri-
 233 butions ($\sigma \geq 30^\circ$; see Fig. 4, dashed line) only because of the relative lack of low inclination objects in these
 234 distributions. The HiLat detected sample, on the contrary, rejects any model with too wide an inclination
 235 distribution because this survey is very sensitive to the high inclination orbits. Even the inclination width
 236 $\sigma = 16^\circ$ preferred by CFEPS has a long tail containing too many objects with $i > 35^\circ$ which would have
 237 been detected by HiLat. But being completely insensitive to low inclination orbits (HiLat cannot detect any
 238 of them), it can accept any values of σ as long as they allow enough objects up to $i \simeq 35^\circ$. Thus HiLat
 239 is consistent with all values of σ from 7.5° to 15.5° (Fig. 4, dash-dotted line). Together, the two surveys
 240 combine high CFEPS sensitivity at low inclinations and HiLat's improved sensitivity at high inclinations.
 241 The result is shown in Fig. 4. Because our model rejection threshold is set at 5% significance, this analysis
 242 indicates that an acceptable value for each of CFEPS and HiLat separately and for their combination, is an
 243 inclination width σ in the range 14° – 15.5° , where all three curves exceed the threshold.

244 Separately, CFEPS and HiLat favor different values for the width and only marginally agree at the
 245 intersection (see Fig. 4). There is tension between the models allowed by the two data sets. This raises
 246 doubts on the parameterization used here. Gulbis et al. (2010) introduced an inclination distribution given
 247 by $\sin(i)$ times a Gaussian of width σ , centered on a value i_c greater than 0° to fit what they called the
 248 Scattered population (Appendix A). Pike et al. (2015) did the same to study the 5:1 MMR population. P1
 249 mentioned the possibility to use a similar functional form to represent the Classical belt hot population
 250 inclination distribution, but concluded that the fit was good enough with the usual distribution and that the

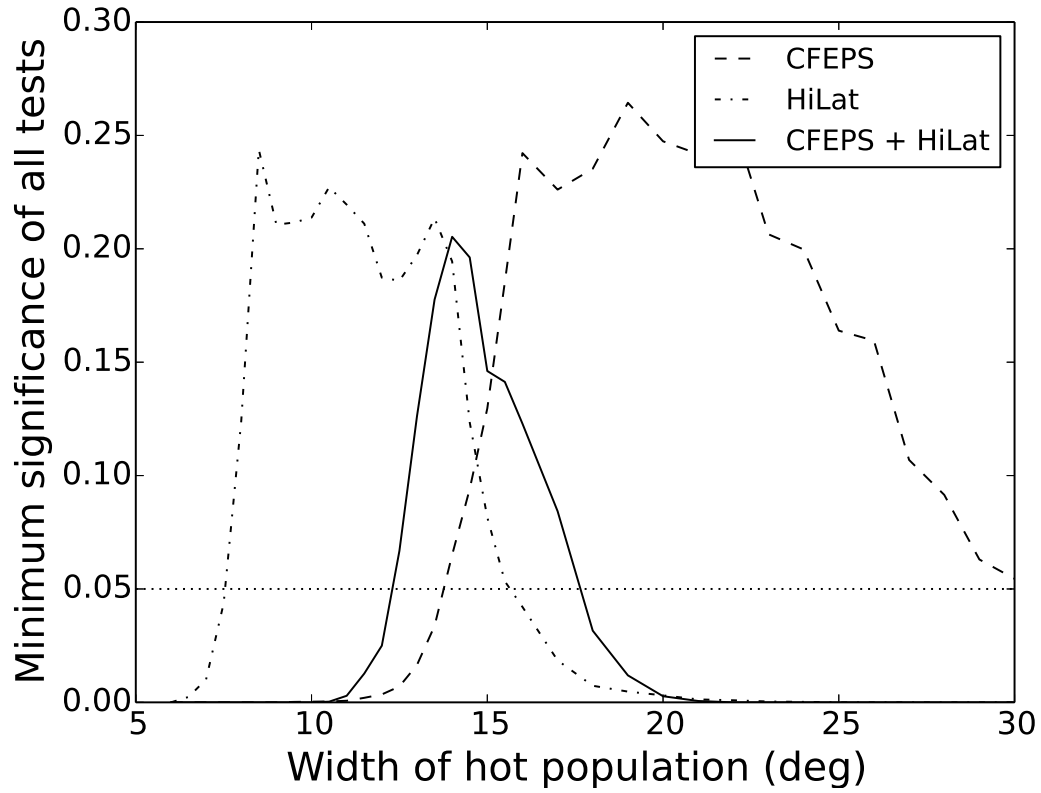


Fig. 4.— Modelling the hot component of the main classical belt. Minimum level of significance of all 6 Anderson-Darling tests for a , e , i , q , R , and r' , as a function of the hot population inclination distribution width, for CFEPS alone (dashed line), HiLat alone (dash-dotted line) and CFEPS and HiLat combined (solid line). The dotted line shows the 95% rejection threshold; any model with significance level below that line is rejected. The bumpiness of the curves is due to randomness in the survey simulator and in the bootstrapping of the Anderson-Darling statistics.

251 data did not demand the increased complexity of the extra parameter. Applying this functional form to the
 252 CFEPS, HiLat and CFEPS+HiLat sample also does not improve the level of significance enough to warrant
 253 the increased complexity of the extra parameter. So our preferred model retains the previous inclination
 254 distribution functional form, with a width $\sigma = 14.5^\circ$. We note, however, that the functional form here,
 255 while useful for discussion, is not a good description of the physical distribution of high-inclination TNOs.

256 5.1.2. Population estimates

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

263 We follow the same procedure as in Kavelaars et al. (2009), Gladman et al. (2012), and P1. We run
 264 our model, generating simulated objects, passing them through the survey simulator until we have detected
 265 the same number of objects in the simulation as in the real survey(s). We record this number and repeat
 266 the procedure 500 times. This gives us the distribution of likely population size. Table 5, columns A, gives
 267 the population estimates, using our new model, to $H_g \leq 8.0$ to compare with P1. Compared to P1, we use
 268 the new q -distribution and an i -distribution with width $\sigma_h = 14.5^\circ$. Our CFEPS estimates are statistically
 269 undistinguishable from P1 estimates.

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

278 Up to now we used the $g' - r' = 0.7$ colour derived from CFEPS sample for all components. However,
 279 the cold belt objects are redder than the hot ones (Doressoundiram et al. 2002; Tegler et al. 2003). If the hot
 280 objects detected by HiLat are bluer than $g' - r' = 0.7$, then the number of objects brighter than $H_g = 8.0$
 281 needed to match the real detections is larger. According to Fraser (private communication, 2016), the cold
 282 component has a typical colour $0.8 < g' - r' < 1.1$, while the hot component comprise mostly neutral objects
 283 with $0.4 < g' - r' < 0.7$, and a small fraction of objects as red as the cold component. Table 5, columns B,
 284 gives the population estimates when using $g' - r' = 0.45$ for the hot component and $g' - r' = 0.95$ for the
 285 cold component. The three population estimates become more compatible with each other, and the fraction
 286 of simulated detections from HiLat in CFEPS+HiLat simulations becomes 7%, similar to the real detected

Table 5. Model dependent population estimates for $H_g \leq 8.0$.

Population	CFEPS		HiLat		CFEPS+HiLat	
	A	B	A	B	A	B
hot	$3,700^{+800}_{-700}$	$3,500^{+700}_{-700}$	$2,100^{+1900}_{-1300}$	$2,700^{+3100}_{-1700}$	$3,500^{+700}_{-600}$	$3,400^{+600}_{-600}$
stirred	$2,700^{+600}_{-500}$	$2,600^{+500}_{-500}$	$1,550^{+1400}_{-950}$	$2,000^{+2300}_{-1300}$	$2,600^{+500}_{-450}$	2500^{+450}_{-450}
kernel	800^{+200}_{-150}	750^{+150}_{-150}	450^{+450}_{-300}	600^{+700}_{-400}	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 H_g limit. The A columns correspond to a uniform colour $g' - r' = 0.7$, while B columns have $g' - r' = 0.45$ for the hot component and $g' - r' = 0.95$ for the cold component.

287 fraction. This result provides (unsurprising) evidence for the already known different $g' - r'$ colours of the
288 various components, which must be accounted for when combining detections in different filters.

289

5.2. Other populations

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

298 The HiLat characterized sample contains 4 resonant objects. One is in the 2:1 MMR and another one
299 in the 5:2 MMR with Neptune. These represent a small contribution to the known populations of these reso-
300 nances from characterized surveys like CFEPS. HiLat made an important contribution to our understanding
301 of the resonant population by discovering two objects in the 5:1 MMR (only 1 was known from CFEPS),
302 and another very close to the 5:1 MMR, HL8k1 = 2008 JO₄₁ at 87.356 AU; scientific interpretation of these
303 discoveries have been reported in Pike et al. (2015).

304

5.3. Exotic objects: 2008 KV₄₂ and (418993) 2009 MS₉

305 Amongst its 21 characterized detections, HiLat discovered 2 extraordinary TNOs. Both are scattering
306 objects. The first one was discovered on May 31st, 2008 in a field at moderate ecliptic latitude ($\sim 30^\circ$). It
307 is HL8n1 = 2008 KV₄₂, the first known retrograde TNO. Details about this object and what it tells us about
308 the origin and dynamical evolution of exotic scattering objects is developed in Gladman et al. (2009).

309 The second object is HL9m1 = (418993) 2009 MS₉, discovered on the 26th of June 2009 at a distance
310 of 12.9 AU from the Sun and an ecliptic latitude of 71° . It has a large ($a \simeq 350$ AU) and highly-inclined
311 ($i \sim 68^\circ$) orbit (Fig. 5), which is also highly eccentric ($e \simeq 0.968$). Inbound at 13 AU at time of discovery,
312 the pericenter of this extreme orbit was ~ 11 AU in February 2013, so (418993) is transiting the range of he-
313 liocentric distances where comets have been observed to become active (Meech & Svoren 2004). (418993)
314 thus may be the first observable object that has been in deep cold storage at hundreds of AU for of order
315 5,000 years. Under the hypothesis that this is a comet from a distant source (either the inner Oort Cloud, or
316 something else as yet unknown), it is also quite possible that (418993) has never been interior to Saturn's
317 orbit (unlikely to be true for the known Centaurs, which often have their perihelia altered as they interact
318 with the giant planets).

319 A plausible scenario is that (418993) is a former Oort-cloud object that has had its orbit changed

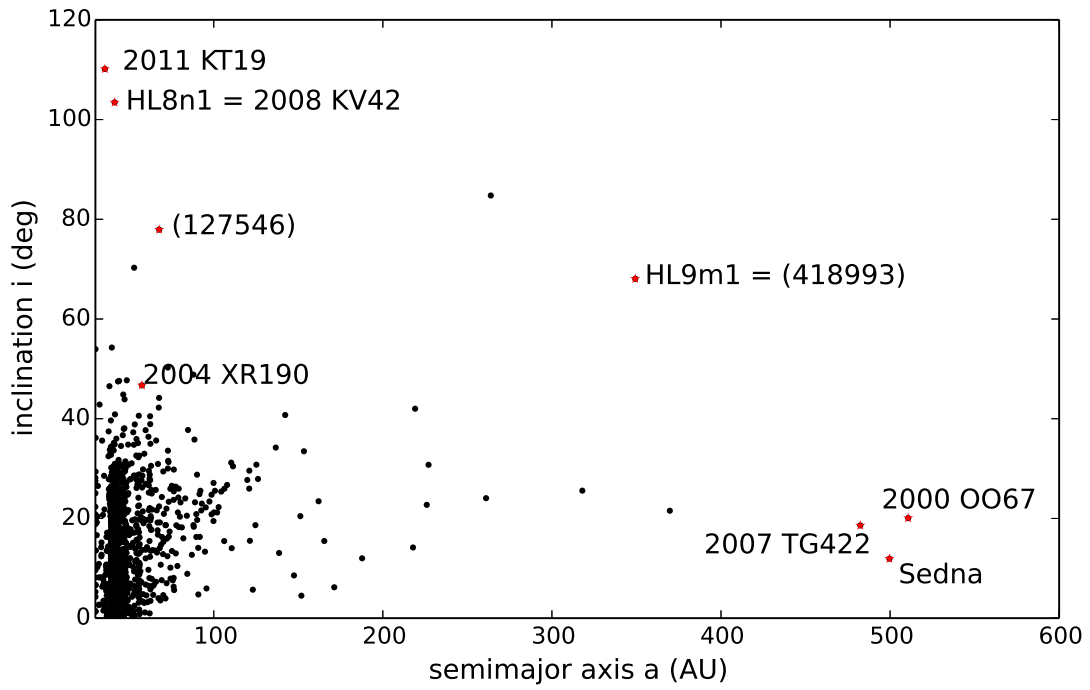


Fig. 5.— Trans-Neptunian objects with $q > 10$ AU in orbital a/i space, in ASTORB database as of August 2nd, 2016. Since its discovery, 2009 MS₉ = (418993) stands out as unique (with other $a > 300$ AU TNOs having inclinations in the ‘normal’ $i < 20$ deg range). 2008 KV₄₂ is also very peculiar with a retrograde orbit almost polar, having only one other object with similar orbit, 2011 KT₁₉.

320 from nearly parabolic ($a > 1000$ AU) to highly eccentric by an encounter with Saturn, Uranus, or Neptune.
 321 (418993) is currently only dynamically meta-stable on the order of ~ 10 Myr, and may never have come
 322 inside the water-sublimation zone (heliocentric distances of 5–6 AU). Many comet nuclei have been studied
 323 after the development of a coma, but only after the comets have left the inner Solar System and are very dim
 324 (Lamy et al. 2004). MS9 had the advantages that, at time of discovery, it was bright ($r' \sim 22$), inbound, and
 325 had no obscuring coma. Assuming an albedo $p=0.04$ (common for comet nuclei, Lamy et al. 2004, but on
 326 the lower end for TNOs), this object has a radius $\simeq 20$ km. Not only is (418993) unique dynamically, but if it
 327 had become an active comet, it would have been the largest comet nucleus in recent times, after Hale-Bopp
 328 (C/1995 O1; radius = 37 km; Lamy et al. 2004).

329 At its discovery distance of 13 AU, no coma has been detected in analysis of our deep August 2009
 330 CFHT images, to a limit of 28 mag/arcsec². Other shorter-period comets have been observed to start
 331 cometary activity as far out as 12–14 AU from the Sun (1P/Halley at 14 AU and 2060 Chiron at 12 AU;
 332 Meech & Svoren 2004). We observed (418993) at the Palomar 5m in August 2009, and determined that it
 333 has a ~ 0.4 -mag lightcurve with a period of over either 6.5 (single peaked) or 13 hours (double peaked;
 334 Fig. 6). Studying a possible cometary activity on this object requires determining the rotational phase to
 335 remove this predictable brightness change. We obtained snapshot observations to monitor the cometary ac-
 336 tivity from Aug. 2010 to Feb 2011 but detected none. From 2012 until end of 2014, many observations
 337 of (418993) have been reported to MPC, around its perihelion passage, but none have reported detection of
 338 cometary activity.

339 6. Summary and discussion

340 The HiLat survey was designed to address one of the shortcomings of CFEPS, its lack of sensitivity
 341 to high-inclination objects. HiLat imaged about 700 sq. deg. from 12° to 85° ecliptic latitude. The survey
 342 was performed at CFHT in the r' filter and achieved limiting magnitudes ranging from $r' = 22.4$ for the
 343 shallowest field to $r' = 24.8$ for the deepest field. Being at high ecliptic latitude, the survey detected only
 344 24 objects, of which 21 are brighter than the characterization limit. Thanks to the small number of objects
 345 and to our careful follow-up strategy, we tracked all characterized objects to precise orbit determination and
 346 orbital classification.

347 HiLat detected 6 objects from the hot main classical belt. We confirm the global parameterization of
 348 this component found by CFEPS. An important finding of CFEPS was that the q -distribution of the hot
 349 classical component is essentially flat between 35 AU and 40 AU, with poor constraint on this upper limit.
 350 The HiLat sample requires us to move the upper limit to 41 AU. Including the HiLat sample and survey in
 351 the analysis, we decrease slightly the width of the inclination distribution of the hot component to $\sigma = 14.5^\circ$.

352 The high sensitivity of HiLat survey to TNOs on highly-inclined orbits permits formal rejection at high
 353 confidence of 'wider' orbital i -distributions for the hot classical belt, and to a lesser extent the detached
 354 components. CFEPS survey already rejected 'narrower' i distributions. Having an i -distribution with little
 355 contribution below about 10° and not extending much beyond 35° – 40° is difficult to achieve with a broad

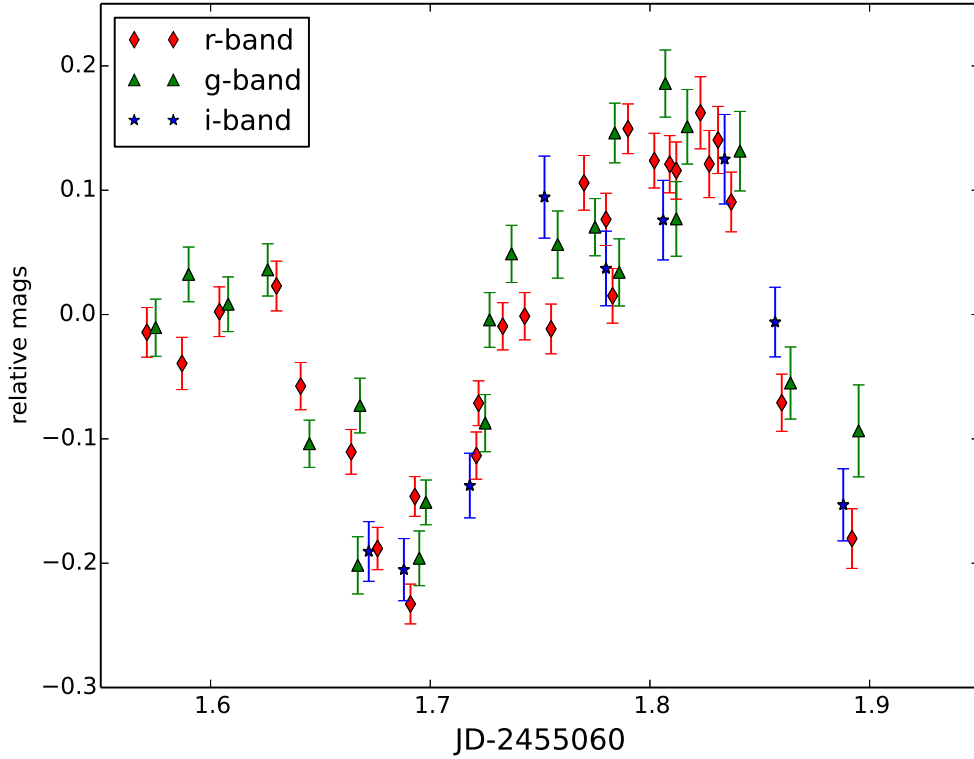


Fig. 6.— Preliminary lightcurve from 18 and 19 August 2009 Palomar data. The magnitudes are relative to 8 field stars (with the mean removed). r-band (red diamond) and g-band (green triangle) photometry was obtained on both nights, while the i-band (blue star) was acquired only on the first night. The r- and g-band magnitudes have been arbitrarily adjusted to the same mean to show that there is no strong rotational colour dependence. The amplitude is ~ 0.4 mag. Observations acquired on the 19 August 2009 have been arbitrarily shifted by 26 hours. This plot shows that the period is around 6.5 hour if single peaked or around 13 hour if double peaked. Although the single peaked solitino seems incompatible with this plot, the quality of the data does not allow to reject it firmly. Thus one needs a longer time span to really characterize the lightcurve.

356 gaussian centered at 0° distribution. It becomes increasingly clear that eq. (7) in Brown (2001) is not the
 357 appropriate representation for this distribution and something different should be considered. The distribu-
 358 tion proposed by Gulbis et al. (2010) is an interesting possibility. A new i -distribution could have profound
 359 cosmogonic implications that would need to be investigated.

360 The exotic higher- i objects like those found in HiLat (Fig. 5) do not fit into this picture; we will
 361 call these $i \sim 90^\circ$ objects the ‘halo’ component. Due to our sensitivity to high inclinations, these do not
 362 represent the tail of the 14.5° gaussian. Instead, these objects may point to a new source that feeds large- i
 363 TNOs into the planetary system (Gladman et al. 2009). This may simultaneously be the source of the Halley-
 364 Type comets (see Levison et al. 2006). Recently, Batygin & Brown (2016) pointed to (418993) as possible
 365 evidence that this source might be related to an undiscovered planet in the distant solar system ($a \sim 500$ au);
 366 producing $a < 50$ objects like 2008 KV₄₂ requires pulling objects from such a large- a source down to such
 367 small semimajor axes and is exceedingly difficult due to the high encounter speeds with Neptune and Uranus
 368 (Gladman et al. 2009).

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

374 A. Appendix A

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

- 377 • a perihelion distance q distribution that is mostly uniform between 35 and 41 AU, with soft shoulders
 378 at both ends extending over ~ 1 AU; the PDF is proportional to $1/([1 + \exp((35 - q)/0.5)][1 +$
 379 $\exp((q - 41)/0.5)])$; any object with $q < 35$ AU is rejected;
- 380 • reject objects with $q < 38 - 0.2i$ (deg) to account for weaker long-term stability of low- q orbits at
 381 low inclination.

382 The inclination distribution for the hot component remains $P(i) \propto \sin(i) \exp(-i^2/2\sigma^2)$, but with $\sigma =$
 383 14.5° .

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