A POSSIBLE DIVOT IN THE SIZE DISTRIBUTION OF THE KUIPER BELT’S SCATTERING OBJECTS

C. Shankman1,2,3, B. J. Gladman1, N. Kaib4,5,6, J. J. Kavelaars2,3, and J. M. Petit7

1 Department of Physics and Astronomy, University of British Columbia, 6224 Agriculture Road, Vancouver, BC V6T 1Z1, Canada
2 National Research Council of Canada, Victoria, BC V9E 2E7, Canada
3 Department of Physics and Astronomy, University of Victoria, BC V8W 3PC, Canada
4 Department of Physics and Astronomy, Queens University, Canada
5 Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, ON M5S 3H8, Canada
6 Department of Physics and Astronomy & Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA), Northwestern University, Evanston, IL 60208, USA
7 Institut UTINAM, CNRS-Université de Franche-Comté, Besançon, France

Received 2012 October 11; accepted 2013 January 8; published 2013 January 22

ABSTRACT

Via joint analysis of a calibrated telescopic survey, which found scattering Kuiper Belt objects, and models of their expected orbital distribution, we explore the scattering-object (SO) size distribution. Although for \( D > 100 \) km the number of objects quickly rise as diameters decrease, we find a relative lack of smaller objects, ruling out a single power law at greater than 99% confidence. After studying traditional “knees” in the size distribution, we explore other formulations and find that, surprisingly, our analysis is consistent with a very sudden decrease (a divot) in the number distribution as diameters decrease below 100 km, which then rises again as a power law. Motivated by other dynamically hot populations and the Centaurs, we argue for a divot size distribution where the number of smaller objects rises again as expected via collisional equilibrium. Extrapolation yields enough kilometer-scale SOs to supply the nearby Jupiter-family comets. Our interpretation is that this divot feature is a preserved relic of the size distribution made by planetesimal formation, now “frozen in” to portions of the Kuiper Belt sharing a “hot” orbital inclination distribution, explaining several puzzles in Kuiper Belt science. Additionally, we show that to match today’s SO inclination distribution, the supply source that was scattered outward must have already been vertically heated to the of order 10°.

Key words: comets: general – Kuiper Belt: general

Online-only material: color figures

1. INTRODUCTION

Measurements of the Kuiper Belt’s size distribution (number at each diameter \( D \)) constrain accretional processes at planet formation and, potentially, subsequent collisional or physical evolution. Because astronomers observe brightnesses rather than \( D \), object absolute magnitudes \( H \) are tabulated as the observable proxy for the size distribution. Collisional and accretional theories suggest exponential forms for the \( N(H) \) distribution. A differential number distribution of the form \( dN/dH \propto 10^{\alpha H} \) with a logarithmic “slope” \( \alpha \) corresponds to a power-law \( D \) distribution \( dN/dD \propto D^{-(5\alpha+1)} \). Although power-law \( D \) distributions provide acceptable fits to Kuiper Belt surveys over spans of a few magnitudes in \( H \), departures from single power laws are necessary over larger \( H \) ranges (Jewitt et al. 1988; Gladman et al. 2001; Bernstein et al. 2004; Fuentes & Holman 2008; Fraser & Kavelaars 2008). For the steep (\( \alpha = 0.8–1.2 \)) distributions seen in the Kuiper Belt, detections are dominated by objects near the largest \( H \) magnitude (smallest size) visible in a given survey. An \( \alpha > 0.6 \) slope cannot continue as \( H \to \infty (D \to 0 \) km) or the total mass diverges; thus a slope change (generically called a break) is required. Evidence of such a break now exists for trans-Neptunian objects (TNOs) in the main Kuiper Belt (at distances \( d \approx 38–46 \) AU), both near the sensitivity limit of ground-based telescopic surveys (Fraser & Kavelaars 2008; Fuentes & Holman 2008; reaching a g-band \( H \)-mag, \( H_g \), of 9–10 at 40 AU) and from deeper Hubble Space Telescope (HST; Bernstein et al. 2004) observations (\( H_x \sim 13 \) at 40 AU). This break has been modeled as a gradual transition to a smaller value of \( \alpha \), a “knee.”

Probing a break is difficult because small TNOs are faint. This problem is reduced when observing the scattering objects (SOs); these are mostly TNOs with perihelia \( q \lesssim 35 \) AU (see below) and thus smaller objects are detectable while near the Sun.

At any time some SOs are only \( d = 20–30 \) AU away, allowing a 4 m telescope, in excellent conditions, to detect objects down to \( H_x \sim 12 \). For a monotonically increasing number distribution \( N(H_x) \), the abundant small objects at the observable volume’s innermost edge should dominate the detected sample. This is not what our survey found (Figure 1), necessitating a relative lack of small SOs.

We discarded a sudden (ad hoc) albedo change, as it would produce a gap in \( H \)-space, not a drop, which does not match the observations; the needed change is a sudden lack of \( H_x > 9 \) (and therefore small) SOs.

2. MODELS

Several models of the SO orbital element distribution were exposed to the calibrated observational biases of the Canada France Ecliptic Plane Survey (CFEPS) in order to quantitatively constrain the intrinsic \( N(H_x) \) distribution. Drawing SOs from an orbital distribution model, and selecting \( H_x \) from a candidate \( N(H_x) \) distribution, the CFEPS survey simulator (Jones et al. 2006) determines each object’s observability and produces a set of “simulated detections” expected from the model.

Two different SO orbital models are from a modified version of Kaib et al. (2011a, 2011b, henceforth KRQ11). KRQ11 focus on the effects of solar migration in the Milky Way on Oort...

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Cloud structure. While this is not the focus of the current work, we can use the KRQ11 control calculations, which assume an unchanging local galactic environment.

To test the sensitivity of our results to the dynamical context, we performed the same analysis on an independent model. Gladman & Chan (2006) modeled the scattering of objects in an initial solar system having an additional planet of the order of Earth mass. As previously reported (Petit et al. 2011), this model also (perhaps surprisingly) satisfactorily represents the current SO \((a, q)\) distribution, although too “cold” in inclinations. In fact, this model and the cold KRQ11 model produced very similar results, showing that our conclusions are mostly insensitive to the assumed solar system history. Objects currently in the Centaur and detectable SO region (mostly \(a < 200\) AU) have, unsurprisingly, almost forgotten their initial state except for the inclination distribution; the current SO orbital distribution is not diagnostic of the number and position of the planets early in the solar system’s history.

### 3. OBSERVATIONS

CFEPS provided a set of detections of outer solar system objects in a precisely calibrated survey (Jones et al. 2006; Kavelaars et al. 2009) whose pointing history, detection efficiency, and tracking performance were recorded. The final set of TNO detections (with full high-precision orbits) and the fully calibrated pointing history make up the L7 release (Petit et al. 2011). This absolute calibration of CFEPS allows a model of the present orbital (and size) distribution to be passed through the CFEPS Survey Simulator, yielding a set of simulated detections whose orbital and \(H_g\) distributions can be compared to the real detections.

The three models provide orbital distributions of all TNOs. The “scattering” TNOs are then selected out of the final 10 Myr stage of the model integrations using the criteria: variation of \(a > 1.5\) AU in semimajor axis during 10 Myr, with \(a < 1000\) AU (Morbidelli et al. 2004; Gladman et al. 2008). Historically, a simple \(q\) cut was used to isolate the “scattered disk” (Duncan & Levison 1997; Luu et al. 1997; Trujillo et al. 2000), which has serious disadvantages when trying to discuss the cosmogony, as there is a nearly impossible distinction between implanted (and thus scattered) and the original Kuiper Belt population (if any). Perihelion divisions also undesirably include resonant objects and most inner main-belt TNOs.

The CFEPS SO sample consists of nine objects (Table 1), supplemented by two SOs discovered in a high-latitude extension survey (covering \(\simeq 470\) deg\(^2\) in 2007–2008, extending up to

### Table 1

| Designation | \(a\) (AU) | \(q\) (AU) | \(i\) (deg) | \(d\) (AU) | \(H_g\) |
|-------------|-----------|-----------|-------------|-----------|----------|
| L4k09       | 30.19     | 24.60     | 13.586      | 26.63     | 9.5      |
| HL8a1       | 32.38     | 22.33     | 42.827      | 31.36     | 7.3      |
| L4m01       | 33.48     | 28.73     | 8.205       | 31.36     | 8.9      |
| L4p07       | 39.95     | 26.31     | 23.545      | 29.59     | 7.7      |
| L3q01       | 50.99     | 33.41     | 6.922       | 38.17     | 8.1      |
| L7a03       | 59.61     | 33.41     | 6.922       | 38.17     | 8.1      |
| L4v11       | 60.04     | 31.64     | 13.642      | 46.99     | 7.1      |
| L4v04       | 64.10     | 38.10     | 13.642      | 46.99     | 7.1      |
| L4v15       | 68.68     | 36.81     | 13.642      | 46.99     | 7.1      |
| L3h08       | 159.6     | 20.26     | 15.499      | 26.76     | 10.0     |
| HL7j2       | 133.25    | 20.67     | 34.195      | 38.45     | 8.0      |
to 65° ecliptic latitude), which was fully calibrated in the same way as CFEPS.

To characterize the form of the $N(H_g)$, we introduce a novel formulation, allowing for the exploration of distributions with knees and divots (a sudden drop in the differential number of objects followed by a recovery). We parameterized the $H_g$ distribution (Figure 2(A)) with the fixed slope $\alpha_b = 0.8$ (see below) for SOs brighter than a break at $H_g = 9$ ($D \approx 100$ km), allowed an adjustable slope $\alpha_f$ for fainter objects, and an adjustable contrast $c \geq 1$.

The $H_g$ magnitudes are drawn from one of the three types of distributions, (1) a single exponential of logarithmic slope $\alpha$: (2) $N(H_g)$ with a knee (contrast $c = 1$). That is, one slope $\alpha_b$ for SOs with $H_g < H_{\text{knee}}$ and $\alpha_f$ for $H_g > H_{\text{knee}}$, where $N(H_g)$ is continuous across the knee at $H_{\text{knee}}$ and negative slopes $\alpha_f$ are allowed as suggested (Bernstein et al. 2004); and (3) one slope $\alpha_b$ to a divot at $H_{\text{divot}}$, which is a sudden drop in differential number by a factor of $c$, with a potentially different slope $\alpha_f$ beyond the cliff at $H = H_{\text{divot}}$. Although in reality the discontinuity is unlikely to be an instantaneous drop, we do not merit trying to constrain the values of the expected steep negative slope and small extent over which it drops; collisional models (Fraser 2009; Campo Bagatin & Benavidez 2012) do show collisional divots where the drop occurs over $D$ ranges of factors $<2$ (a few tenths of magnitude in $H_g$).

In principle, there are four parameters: $\alpha_b$, $\alpha_f$, $H_{\text{divot}}$, and $c$ (Figure 2). For $H_g < 9$, a single power law of $\alpha_b \simeq 0.8$ does indeed match our detections; we elected to fix this slope at that value with the unifying philosophy that all the hot trans-Neptunian populations share this same hot slope; $\alpha_b = 0.8$ matches both the hot Classical belt measured down to $H_g \simeq 8.0$ (Fuentes & Holman 2008; Fraser & Kavelaars 2009; Petit et al. 2011), and to the 3:2 resonators measured down to $H_g \simeq 9.0$ (Gladman et al. 2012). Our detections require a transition around $H_g = 9–10$ to explain the relative lack of small detections; we thus fixed the knee/divot for our analysis at $H_g = 9$ (slightly larger than $D = 100$ km for 5% g-band albedo). This leaves only two free parameters: the contrast $c$ at the divot and the slope $\alpha_f$ for absolute magnitudes fainter than the divot/knee.

To assess a match, the Anderson–Darling (AD) statistic is calculated between our 11-object sample and the distribution of simulated detections from the model, for each orbital parameter. An AD significance level of $<5\%$ rejects the hypothesis that the real SO observations could be drawn from the simulated detections at the 95% confidence level (for that orbital parameter). To retain a model, we required that none of the $q$, $d$, $i$, and $H_g$ distributions are rejectable at $>95\%$ confidence.

4. ABSOLUTE MAGNITUDE DISTRIBUTION

The observational bias is strong (Figure 1), but when accurately calibrated allows us to constrain the $H_g$ distribution’s form. Single power laws predict significantly more close-in detections than were seen by CFEPS; for a slope of $\alpha = 0.8$, roughly half of the expected detections (blue dashed curve in Figure 1(D)) should have a distance at detection $d < 23$ AU, which is the closest real SO in our sample. The observationally biased models predict that the majority of detected SOs would have orbits with $q < 20$ AU at $d = 20–25$ AU and be small ($H_g > 9$ or $D \leq 100$ km) objects, in contrast to our detections, which demonstrates that our observations are sensitive beyond the break. When confined to $q > 25$ AU (where objects must be large to be seen), the orbital models provide good agreement with our data.
matches, however, extensions to smaller distance fail when using a single power law, pointing to a breakdown arising from the assumed $N(H_g)$.

We rule out a single power law of slope 0.8 at 99% confidence and can rule out all single power laws with slope between 0 and 1.2 at 95% confidence. Slopes of 0.5 and 0.6 are not rejectable across the whole distribution, but are rejectable (95% confidence) when the distribution is considered in both $H_g > 9$ and $H_g < 9$ subsets; we demand these work because the steep slopes measured for other hot populations match our $H_g < 9$ detections well, and a shallower slope is erroneously found by measuring across a divot feature when requiring a single slope (see below).

Our relatively small sample is powerful because our detected SOs span the break and, when coupled with the precise CFEPS calibration, allows the non-detection of $H_g = 10$−$12$ SOs (several magnitudes past the divot) to provide a strong constraint on $N(H_g)$. Down to this limit, CFEPS detected moving objects as close as 20 AU with no rate of motion dependence. Because our orbits are accurate, we can separate the SOs from the other hot populations, and use a dynamical model specific to the SOs.

All of our $N(H_g)$ cases have the obvious and previously known problem that the model’s orbital inclinations are mostly lower than the true population’s (Petit et al. 2011; Gladman et al. 2012), even for the cases where the $N(H_g)$ otherwise provides a good match. For example, Figure 1 shows a divot ($c \approx 6$, $\alpha_f = 0.5$) producing a good match between the model’s expected detections (green curve) and the real SO sample (red), excepting the $i$ problem. Models (Levison et al. 2008) that scatter out a cold TNO population (from $d < 30$ AU with initial inclination distribution widths $\sigma_i \lesssim 6^\circ$) to eventually form today’s hot population produce current TNO populations where too many low-$i$ detections are expected in observational surveys (Figure 1(B)). This is part of growing evidence that the original Kuiper Belt populations.

The so-called hot Kuiper Belt populations (the hot main belt, inner belt, resonant, and detached TNOs) share an $i$ distribution half-width of roughly $15^\circ$ (Petit et al. 2011) with the SOs, suggesting a cosmogonic link. In analyses of deep luminosity functions dominated by hot main-belt detections, the common conclusion (Bernstein et al. 2004; Fuentes et al. 2010) was that for magnitude $g > 25$ the slope must break to a faint $\alpha_f < 0.3$ value or even become negative in order to explain the lack of detections in the following few magnitudes; beyond this no data exist for the main Kuiper Belt. For SOs and their companion objects (Centaurs), however, many $H_g > 9$ objects are known from wide-field surveys, mostly detected at $d < 20$ AU. In fact, measurements of Jupiter-family comets (JFCs) in the $H_g \approx 14$−$17$ range give slopes $\alpha_f \approx 0.5 \pm 0.1$ (see Table 6 of Solontoi et al. 2012). These two arguments mean that the SO distribution cannot remain at $\alpha_f < 0.3$, leading us to discard knees to negative slopes. A divot can explain both a relative lack of

Figure 3. Hot (black dashed) and cold (light-blue dashed) KRQ11 intrinsic $i$ distributions produce the biased distributions (solid lines) from our preferred model for comparison with the CFEPS sample (red). The hot model significantly improves the match because it has a relative lack (at the current epoch) of low-$i$ SOs to be detected by the survey: the 11 CFEPS SOs have $H_g$ > 0 and 1.2 at 95% confidence. We therefore computed a new SO model with a hotter ($\sigma_i \simeq 12^\circ$) initial disk; this provides an excellent match with today’s SO $i$-distribution (see Figure 3) and we constrain $N(H_g)$ below using this model.

To constrain the size distribution, a grid of possible divot contrasts and post-divot slopes was explored. Figure 4 shows acceptability levels for the range of explored parameter pairs ($c$, $\alpha_f$). A single power law of $\alpha = 0.8$ (blue star, Figure 4) has <1% probability. We are left with a range of acceptable parameter space, including knee ($c = 1$) and divot ($c > 1$) scenarios; we further constrain $N(H_g)$ by looking to other Kuiper Belt populations.

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Sheppard & Trujillo (2010) used Neptune Trojan searches to project to all other resonant populations (Gladman et al. 2012). Although not yet precisely measured, links these ob-
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such a transplant process can successfully implant TNOs in the
stable Kuiper Belt (Levison et al. 2008; Batygin et al. 2011),

Thus share the same size distribution, we confirmed that our
divot N(H_g) matches the lack of D < 100 km Neptune Torjan
detections in the Sheppard & Trujillo (2010) surveys.

Given our analysis, the conclusion would not be that small
Neptune Trojans are “missing,” but rather that the sudden drop
results in the population fainter than the divot not recovering in
on-sky surface density until at least H_g > 11, by which point the
deepest survey lacked the sensitivity to detect them. If correct,
detection of several small (H_g > 11) Trojans requires surveying
~100 deg^2 to 26th magnitude at the correct elongation.

5. EXTERNAL ARGUMENTS

As the hot populations have similar colors and D > 100 km
size distributions, it seems likely that they were all transplanted
to join a pre-existing cold Kuiper Belt (Petit et al. 2011) during
a common event early in the solar system’s history, and would
thus logically share the same divot and small D distribution.

Such a transplant process can successfully implant TNOs in the
stable Kuiper Belt (Levison et al. 2008; Batygin et al. 2011),
although the resonant population ratios and i distribution are
problematic (Gladman et al. 2012). We thus look for evidence
of such a feature in other hot populations.

6. FEASIBILITY OF A DIVOT

A recent deep telescopic survey (Fraser et al. 2010) estimated
\( \alpha \approx 0.40 \pm 0.15 \) (within error of our preferred \( \alpha_f = 0.5 \)) from
the apparent-magnitude distribution for “close” (30 < d < 38)
TNOs (orbits were not obtained). These distances are dominated
by several hot populations, but the measurement is shallower
than the usual hot population slope of 0.8. We calculated H_g
magnitudes for the Fraser et al. (2010) detections and find that
due to the survey’s depth, this sample is dominated by H_g > 9
TNOs and thus would measure the post-divot slope.

5.1. The Neptune Trojans

A search for Neptune Trojans (Sheppard & Trujillo 2010)
provided significant evidence that an \( \alpha \approx 0.8 \) power law cannot
continue for D < 100 km Trojans; a divot was not apparent
because Trojans significantly smaller were not detected. The
dispersed Trojan inclination distribution (Sheppard & Trujillo 2006),
although not yet precisely measured, links these objects to all other resonant populations (Gladman et al. 2012).

Sheppard & Trujillo (2010) used Neptune Trojan searches to ar-
00 km Neptune Trojan divot size are set by planetesimal formation
physics; smaller objects appear only later due to collisional
fragmentation. These scenarios match our results, where one
interprets the hot population’s N(H_g) to have been “frozen”
when suddenly transplanted (scattered) from a denser region

5.2. Hot Populations

A recent deep telescopic survey (Fraser et al. 2010) estimated
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nearer the Sun to the large volume it now occupies, ending the collisional evolution. An exciting prospect is that the divot directly records a preferential \( D \) that planet building produced in the solar-nebula region where the hot TNOs originally formed, and that the divot’s depth (which could easily range from \( c = 2–30 \)) measures the integrated collisional evolution (depending on both the duration of the pre-scattering phase and the random speeds present). An initial distribution with no \( D < 100 \) km TNOs was shown (Campo Bagatin & Benavidez 2012) to evolve into a divot with \( c \sim 20 \) and \( \alpha_f \simeq 0.5 \), in the dynamical environment of the Nice model; such a 500 Myr quiescent phase (Gomes et al. 2005) allows a divot to form but the evidence we find for a higher-\( i \) early phase may argue instead for a much shorter and more intense collisional environment.

Our divot \( N(H_g) \) produces a cumulative distribution (Figure 2(B)) with a shallow plateau for \( H_g = 9–12 \), similar to that deduced for the hot population and SOs in deep \( HST \) observations (Bernstein et al. 2004; Volk & Malhotra 2008) and estimated for scattering impactors of the Saturnian moons (Minton et al. 2012). Our estimate of \( 2 \times 10^6 \) SOs with \( H_g < 13 \) and a slope of \( \alpha_f = 0.5 \) extrapolates to \( \sim 2 \times 10^6 \) SOs with \( H_g < 18 \), providing a sufficient number (Duncan & Levison 1997; Levison et al. 2001; Volk & Malhotra 2008) of SOs to feed the JFCs, while satisfying the observed plateau.

Single power laws that fit the \( H_g < 9 \) SOs fail when extended to smaller objects. Our novel divot parameterization (Figure 2) matches our data and would simultaneously explain the puzzles of the JFC source, the “missing” Neptune Trojans, and the known rollover in the Kuiper Belt’s luminosity function. To better constrain the form of the break, a new survey must find and determine orbits for \( \sim 10 \) SOs from 10–30 AU; this requires discovery (and tracking over several degrees of arc) targets moving up to \( 15'' \) hr\(^{-1} \) by observing \( \sim 200 \) deg\(^2 \) to 24th magnitude.

Facility: CFHT

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