CFHT [2013A - 2016B] Large Programs
First Call - Deadline: 28 Feb 2012 - 23:59 UTC

Title:	OSSOS: the Outer Solar System Object Survey

Abstract: Progress in studies of planet formation and migration are exhausting the available Kuiper Belt data set. There are simply not enough objects detected in well-calibrated samples to judge the veracity of proposed models of planet formation, initial radial planetesimal distribution, and migration distances or time scales. We propose a 4-year program to find and track more than 1000 trans-neptunian (and closer) objects in our outer Solar System using MEGAPRIME. Due to the proven flexibility provided by CFHT QSO's implementation of Megaprime's capabilities, CFHT is the *only* wide field telescope that is realistically able to provide the data to build such a sample. Because precise orbit determination is vital to the science goals which choose between theoretical models, tracking large sky patches (21 square degrees each) will allow OSSOS to provide a data set that is many times more powerful than existing data sets. By focussing on the sky's resonant sweet spots, we will maximize the science impact of our detected sample. OSSOS will allow the CFHT community to lead the world in this field during this decade.

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Total number of **hours** requested: 560

Hours per agency:	Canada 265	France 265	Hawaii 0	Brazil 0	China 0	Taiwan 30

Hours per semester:	13A 70	13B 70	14A 70	14B 70	15A 70	15B 70	16A 70	16B 70

Proprietary Period (Community): Due to the moving-target exploitation nature of the work, we request a 6-month proprietary period on a per-exposure basis. However, any community members who wish to exploit the OSSOS data set for any science goal not already covered in the OSSOS science Topic Teams will be allowed to contact us and join the collaboration for that science exploitation, getting immediate access to the data.

Proprietary Period (World): The usual proprietary period (release one year after the end of the semester in which the image is taken) is acceptable.

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1 Scientific Justification

Two decades of theoretical and observational effort in outer Solar System science have provided a wealth of new facts, but has left many basic questions unanswered. In fact, observerations have repeatedly revealed totally unexpected new classes of objects which did not appear in models and thus generate profound cosmogonic implications. At the tri-annual Trans-Neptunian Object (TNO) meeting in 2010, the scientists of this community came to the conclusion that further progress on fundamental questions could only be made with a large new concerted effort to acquire a new well-understood TNO sample focussed on the most cosmogonically-important sub-populations, which could be expoited in various ways. The Outer Solar System Origins Survey (OSSOS) team was thus formed, consisting of a large group of motivated observers in the field, reinforced by solid theoretical support.

1.1 Background

Several Kuiper Belt surveys broke ground by investigating the gross properties of the TNO diameter and orbital distributions (Jewitt et al., 1996; Gladman et al., 2001; Millis et al., 2002; Trujillo et al., 2001). However, the dynamical structure is much more complex than anticipated with much fine detail present; surveys with known high-precision detection efficiencies and which track essentially all their objects (to avoid ephemeris bias Jones et al., 2010) are needed to disentangle these details and the cosmogonic information they provide. The Very Wide component of CFHT Legacy Survey was intended to address this, but CFHT TAC members will know it was scaled back in 2004 due to MEGAPRIME's hours/night being less than anticipated. The remaining solar system effort devolved to the *Canada-France ecliptic plane survey (CFEPS)*, *www.cfeps.net* which, although producing solid science contributions to Kuiper Belt science, (Kavelaars et al., 2009; Petit et al., 2011; Gladman et al., 2012) discovered and tracked only 169 TNOs instead of the 1300-object goal of CFHLS-VW. The experience gained along the way shows that such a survey *is* the future of Kuiper Belt science; much remains to be done. The OSSOS survey is thus intended to finally be the Kuiper Belt survey the field needs, and will be THE major undertaking in the field this decade. Our considerable experience in Kuiper Belt science over the last 20 years (including CFEPS) establishes that surveys not optimized for outer Solar System cadence will not meaninfully multiply the current orbital database, and thus will have negligible impact.

Because this science is unfamiliar to many TAC members, we sacrifice some proposal space to a brief primer. The TNOs on low-eccentricity (e) low-inclination (i) orbits with semimajor axes a=35–48 AU were originally referred to as the Kuiper Belt, but because the Kuiper belt quickly became more com-

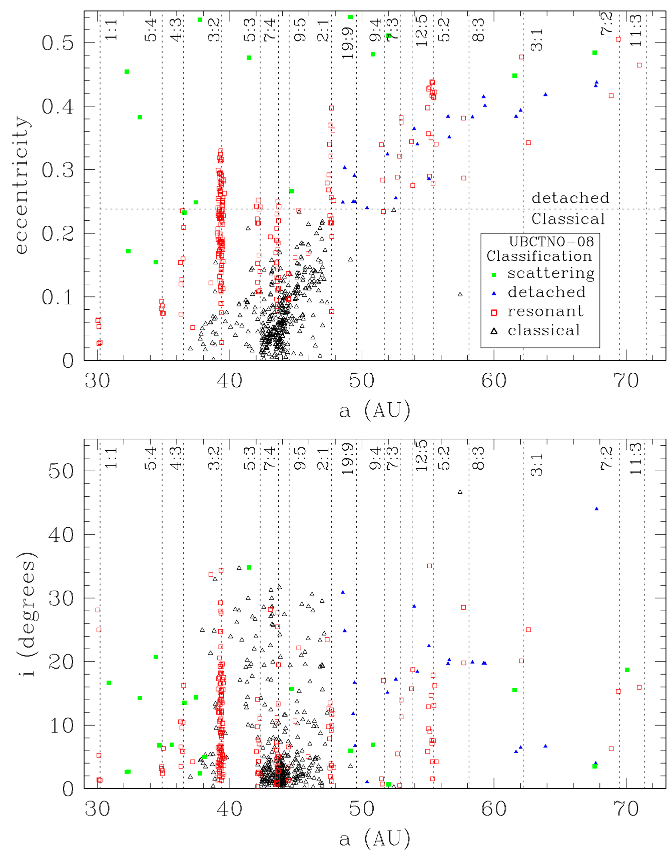

Fig. 1: Orbital element diagram for the a=29–73 AU Kuiper Belt, showing the rich dynamical structure needing to be cosmogonically explained. The Centaurs are scattering objects between the giant planets to the left of this figure, while the detached, scattering, and resonant populations continue off the upper right at larger a and e. Some extreme-inclination objects ($i > 50°$) are off the top of this plot. This figure has extreme detection biases, and the true distributions have many more large-a, large-i, and low-e TNOs than shown here.

plex, are now call the *classical belt*. It seems this must be a primordial feature, and CFEPS exposed that there is radial structure that must be explained. The main belt from a=42.5–47.5 AU is dominated by a narrow inclination component (of width $i \simeq 2.5°$) that exists only in this narrow semimajor axis range; this 'cold' belt is redder, has more binaries, and has a steeper size distribution than the rest of the Kuiper Belt. In contrast, all other Kuiper Belt components share a colour distribution which is bluer, a shallower size distribution for D=200–2000 km, and have TNOs with bigger orbital eccentricities and a much 'hotter' i distribution (gaussian width $\sim 15°$, with outliers beyond $i = 40°$). This hot population is where the critically-important set of *resonant TNOs* exist, which are trapped in mean-motion resonances with Neptune at fixed semi-major axes; the manner in which these resonant objects were emplaced is one of the key questions in outer Solar System science, as it is intimately related to how and where the giant planets formed and migrated. The very transient *Centaur* $a < 30$AU and longer-lived *scattering* $a > 30$ AU populations of TNOs are currently strongly interacting gravitationally with the giant planets; these unstable orbits (believed to link the nearby Jupiter-family comets to their source reservoir) are either the slowly-decaying remnant of a vast population emplaced early in the Solar System's history when the Oort cloud was built, or the steady-state intermediary due to leakage from a more stable Kuiper-belt or Oort cloud population. Lastly the *detached* population consists of stable non-resonant objects with large a and e but whose perihelia are large enough that they are not interacting with Neptune (Gladman et al., 2002).

1.2 Overarching questions:

1: There are the two heavily-discussed physical mechanism in Kuiper Belt science to create resonant TNOs. Were they trapped from pre-existing low-e orbits and then 'pumped' to higher e during subsequent migration? (the Malhotra mechanism, Malhotra, 1995; Hahn & Malhotra, 1999; 2005) Or were they trapped into the resonances out of a scattering population and then had their e's cycle down? (Nice model: Gomes, 2003; Levison et al., 2008)
2: In the latter case, the entire hot population was transported from inside 30 AU to its current location; can this be done without destroying the cold classical belt and the binary populations? How is this related to the dichotomy of the colour (and perhaps albedo) distributions of these populations?
3: Are the scattering TNOs simply a decaying remnant of a huge primordial population emplaced during the giant planet's final migration? Or are they in steady-state with a loss rate balanced by feeding from a meta-stable source (like leakage from the resonant populations, or input from the inner Oort cloud)? Are the ultra-red colours of some of the largest-a objects primordial, or are they created during the long periods where these objects are far from the Sun?
4: How did the detached get their perihelia raised? Some (Gomes et al., 2008) suggest that these are objects which were temporarily resonant, but during planet migration they were dropped off. Others hypothesize (Ida et al., 2000; Brasser et al., 2006; Kaib & Quinn, 2008) that during the Oort-cloud creation phase the Sun was still in an open cluster and passing stars raised the perihelia of scattering objects, especially for the larger-a objects, like Sedna.
5: A few other exceptional TNOs have been found: 2004 XR_{190}, aka. Buffy, (Allen et al., 2006) with a=57 AU, e=0.1, and $i = 47°$, is too tightly bound to the planetary system to sensibly be produced by stellar encounters. Sedna, with $a \sim$500 AU, never approaches the Sun closer that 75 AU; some (Brown et al., 2004) view this as an object related to the Oort cloud while others consider it an extreme detached TNO. Objects on $i > 50°$ or even retrograde orbits like Drac (Gladman et al., 2009) scattering objects also exist. Their existence has profound cosmogonic implications which still lack generally- accepted explanations.

1.3 The OSSOS survey

We propose to exploit the superb CFHT QSO system to acquire a set of synpotic observations in the cadence needed to yield >1000 TNO orbits in a superbly-calibrated outer Solar System survey addressing many science topics. Because the timing between almost all of our exposures has great flexibility (see Technical section), and because the amount of time needed in any given dark run is a small fraction of the available dark time, the ability of CFHT to acquire these exposures via QSO vastly increases the ability to acquire a large sample of high-precision orbits. Although CFHT+MEGAPRIME depth×FOV is now no longer the best in the world, it is the ONLY wide-field imaging telescope on the planet with the ability to reliably acquire this data set; many members of this collaboration have been thwarted in their science when trying to acquire decent-quality orbits using other telescopes. CFEPS showed that the key is to image large contiguous patches of sky ($\sim 20\square°$) and track *all* the TNOs present by slowly drifting the patch over 5 months at the Kuiper Belt rate, and then repeating this the following year. By focussing on selected regions of sky (relative to Neptune) OSSOS maximizes the detection rates of the critical resonant TNOs.

1.4 Primary Science Cases

Length constraints make it impossible to cover in depth all the science that this data set will allow. Almost all of the primary and secondary science cases are greatly strengthened by the fact that the main data product of this highly-characterized survey will not just be the detection list, but also a OSSOS Survey Simulator (see Tech section) which will allow statements about intrinsic properties of the belt (coming from either numerical simulations or proposed distributions of quantities like colour, binary fraction, or size) to be rigorously compared to the detections. Without this kind of detailed understanding, even samples factors of several larger have been unable to make the kinds of precise statements about orbital structure that CFEPS and its survey simulator were able to. Without such exceedingly well-calibrated surveys, quantitative tests of planet-formation models cannot be made.

1.4.1 Resonant structure

The resonant TNOs are the most useful objects for diagnosing the history of the outer Solar System because their orbital parameters encode detailed information, and the distribution of these parameters varies with the timing of planet formation and the method of Kuiper Belt emplacement. The dynamics of a mean-motion resonance are encoded in the resonant angle $\phi_{jk} = j\lambda - k\lambda_N - (j-k)\varpi$ where (somewhat loosely) ϖ is the perihelion longitude of the TNO (along the ecliptic), $\lambda = \mathcal{M} + \varpi$ is angular position along the orbit with $\mathcal{M}$ being the mean anomaly measured from perihelion, and λ_N is the same quantity for Neptune. For the 3:2 resonance (for eg.) ϕ_{32} averages to zero meaning that Neptune orbits 3 times for each two rotations of the TNO, and the phase relationship maintained results in the TNO never being at perihelion in the direction of Neptune, allowing TNOs to actually approach the Sun interior to Neptune. Resonant objects do not have ϕ_{jk} uniformly distributed, but rather it varies (librates) with some *libration amplitude* A_ϕ around a mean value. For many resonances this mean value is 180° ('symmetric librators') but especially for the $n:1$ resonances the mean can take on other values. The resonant angle then confines the on-sky locations of perihelion relative to Neptune, which introduces complex biases into the detection process (Gladman et al., 2012).

For example, the 3:2 librators (visible in Fig 1) at $a \simeq 39.4$ AU exhibit libration amplitudes A_ϕ up to about 130°, with an A_ϕ distribution that CFEPS showed was inconsistent with being flat and instead is peaked near 95°. A product of the CFEPS survey (and OSSOS, see Data Management) is a Survey Simulator (Jones et al., 2006) which subjects a theoretical model (of the orbital and size distribution) to the same calibrated detection and tracking biases that the observational survey suffered, allowing quantitative statistical statements to be made. For example, 3:2 emplacement in a version of the Nice model produces an orbital distribution that, when biased for the survey pointing history and flux biases) agrees for the e distribution, but not for the i (Fig2) or A_ϕ distributions. The conclusion is that the primordial orbital distribution must be more heated in inclination and that the capture process did not happen as this model predicted.

These kind of comparisons are what will allow progress to be made in the next decade in understanding the timing and location of giant planet formation and migration relative to the initial small-body populations that are now present in the Kuiper Belt. While there are a huge number of questions that can be posed, we concentrate on two major ones that OSSOS will address.

1.4.2 Resonant population ratios

There is already known occupancy in resonances ranging from the 1:1 (Neptune Trojans) at 30 AU out the 27:4 at a=108 AU. The pattern of resonant TNOs (the population trapped in each resonance as one moves to larger a) is different for each cosmogonic process. For example, the 2:1 and 5:2 are other resonances (see Fig. 1) which can efficiently trap large numbers of TNOs (like the 3:2). In one model of smooth outward migration (Hahn & Malhotra, 2005) the population ratio expected in the 3:2/2:1/5:2 resonance trio is 2/5/1 respecitively, due to the great efficiency of 2:1 trapping. In models like the Nice model (Levison et al., 2008) the closer resonances are favoured, giving a ratio of 8/3/1. CFEPS (Gladman et al., 2012) measures a ratio pattern of 4/1/4, which agrees with neither of these models because in reality the 5:2 population is larger than that of the 2:1 (at >95% confidence), with a best estimate being four times more populated.

This recent result has profound implications for the trapping process or the heliocentric planetesimal distribution at the time of resonant trapping. Other resonances (especially the 3:1 and 5:1) have such large semimajor axes that <1% of a fux-limited sample is expected to be in these resonances and tracking biases against their eventual identification are severe (Jones et al., 2010). Even with this, the few objects known indicate (Gladman et al., 2012) that the population in dis-

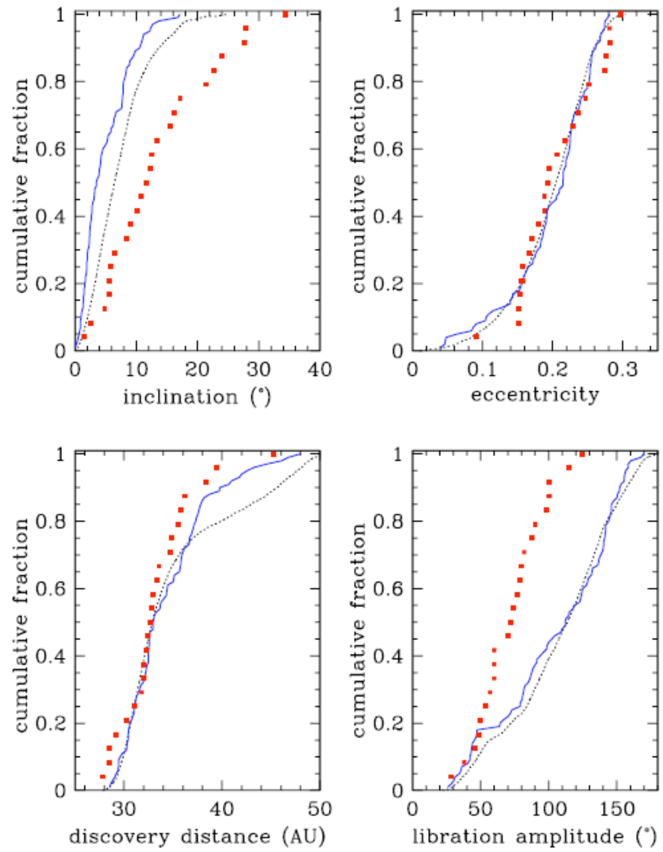

Fig. 2: Comparison of the results of a Nice-model simulation's orbital distribution of 3:2 resonators to the Canada-France-Ecliptic Plane Survey's (CFEPS) detections. In each case the dotted black curve shows the model's cumulative distribution of that quantity while the blue curve shows the expected detections (given that model) when biased by the known pointing and flux history of the previous survey. In this case the e and discovery distance distributions are statistically acceptable, while the libration amplitude and inclination distributions are rejected at >99% confidence.

tant resonances may even exceed the nearby ones, but only an object sample the size of OSSOS (4–10 times more fully-tracked orbits) will be able to confirm this and reliably measure (to say 30% fractional accuracy) the population ratios to the more well-determined 3:2 population.

1.4.3 Constraining planetary migration

Although the theoretical literature has often been framed as an either/or choice between smooth outward Neptune migration, or scenarios where Neptune suddenly jumps to near its present location from further in, it seems reasonable that both processes were of importance in the history of our outer planetary system. The timing of these processes influences the efficiency of trapping and where in the resonance libration-amplitude spectrum the objects are ultimately lodged. The 2:1 is especially important because its stable phase space is separated into three portions: the symmetric librators (like most other resonances) and two asymmetric islands whose occupants come to perihelion at two different locations (leading and trailing) relative to Neptune and can thus be separately measured. Migration models (Chiang and Jordan 2002) show that trapping into the two asymmetric islands is not equally efficient, and depends on the rate and distance Neptune migrated. Fig. 3 shows two models, both of which also exhibit this leading to trailing asymmetry, but which different in the fraction of all 2:1 TNOs that are in the large-amplitude symmetric state. Due to the proximity of the trailing island to the galactic plane (requiring well-calibrated survey efficiencies) and the small number of 2:1 resonators detected, surveys have been unable to even rule out equal occupancy for the two islands (Murray Clay & Chiang, 2005; Gladman et al., 2012).
OSSOS is the first survey that will have enough 2:1 detections (with a precision calibration of the leading vs trailing tracking efficiency), to even in principle be able to measure a non-equal asymmetric population ratio (this cannot be done at 95% confidence without roughly >20 2:1 resonators because some fraction will be symmetric librators). The entire CFEPS survey only yielded five 2:1 resonators, so a sample many times larger will be needed. With an estimated ~ 40 2:1 resonantors detected by OSSOS, even if half were symmetric resonators the asymmetry (and thus detection of ancient planet migration) will be possible.

1.4.4 Main belt size and orbital distribution

The hot and cold components of the main belt (a=40–47.3 AU) are well established. However, sub-structure is now evident in the cold population (Petit et al. 2011) which preserves primordial information under the hypothesis that this component could only maintain its peculiar colour, inclination, and binary-fraction distribution if it formed where we see it today.

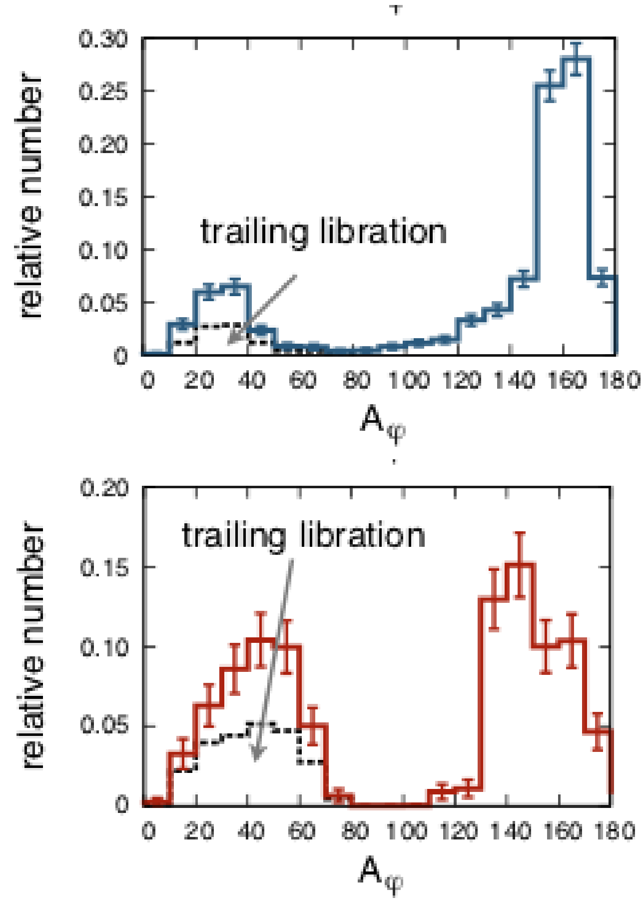

Fig. 3: 2:1 libration amplitude distributions from a 7-AU smooth migration into a pre-existing Kuiper Belt (top) or a short (2-AU) migration into a scattering population (bottom) which traps 2:1 resonantors. Amplitudes $A_\phi > 80°$ are symmetric librators, while smaller A_ϕ means asymmetric libration with the dotted histogram applying to the smaller trailing librator population.

A concentration of orbits in the a=43±1 AU region at low-e and i was initially posulated to be a large collisional family (Chiang, 2002) but the concentration and along with the sheer size and number of objects seems to preclude the collisional breakup of a planet as the likely explanation (although such an origin for the Haumea family is being pursued. (Brown et al. (2007); Leinhardt et al. (2010)) OSSOS will acquire hundreds of classical main-belt objects, and will provide an extremely well-calibrated examination of the orbital and size distribution. Such knowledge will be a very constraint for theories, which must leave this structure intact while simultaneously implanting the resonant and scattering populations.

1.4.5 The Scattering population

OSSOS should detect ~ 40 new scattering TNOs, from which this population's inclination and size distribution can be measured. (This detection rate is more uncertain than the other populations because scattering objects are often found interior to Neptune and are thus on average smaller; uncertain-

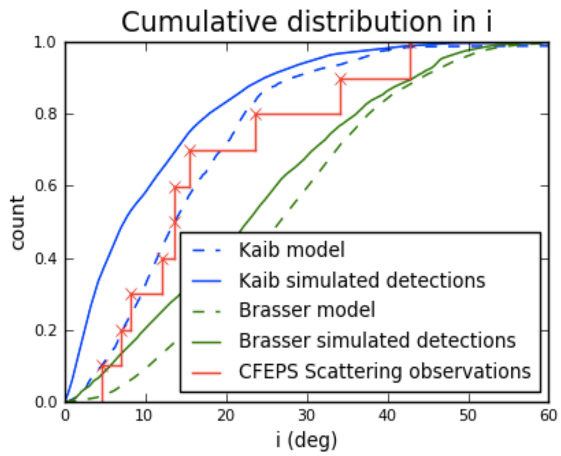

Fig. 4: The inclination distribution depends on whether the scattering population was generated by simple scattering of the planets in their current locations (updated by Kaib et al 2012 similar to Duncan and Levison 1996) or having the giant planets pass through an early dynamical instability like the 'Nice model' (Brasser and Morbidelli 2012). Dashed curves are the intrinsic i distributions from these two models which, when subjected to the known pointing history and calibrated efficiencies of the CFEPS survey simulator, would results in the detected samples (solid curves) being concentrated to smaller i. The small CFEPS scatterign sample (red distribution) is intermediate between that expected from these two models, with the instability model (Brasser) providing a better match. Samples many times larger are needed to make further progress.

ties related to the extrapolation of the diameter distribution mean there is a 50% uncertainty in the detection rate). It is widely thought most such TNOs were generated during a major episode of planetesimal scattering off the giant planets early in the solar system's history, (Duncan & Levison, 1997; Levison et al. 2008) and the population has been steadily dynamically eroded by planetary perturbations. The remaining scattering population thus provides constraints on the Solar System's early history (see Figure 4). An increased scattering sample from OSSOS (CFEPS had only 8) will allow ruling out certain existing models of the planetary orbital histories at high confidence and tuning future ones.

Because the Centaur and scattering populations are strongly biased to be detected interior to Neptune, one is sensitive to smaller objects. Given that these objects are recent dynamical immigrants from the region beyond Neptune, they probe the diameter distribution of the more distant scattering population. Recent work (Fraser et al., 2009; Petit et al., 2011) indicates that the detected scattering/hot TNO sample has a flatter size distribution at these smaller diameters, similar to that shown in the Jupiter-family comets that they are thought to supply. (Solontoi et al 2012; Volk & Malhotra, 2008) These data will allow better estimates of the scattering disk mass, which provides another crucial constraint on the mass of the protoplanetary disk and the orbital history of the giant planets (since it was these planets that generated this reservoir). Finally, although most of these bodies belong to the 'traditional' scattering disk, there are a few obvious outliers in terms of both inclination and semimajor axis (Gladman et al., 2009; Brasser et al., 2012), and the Oort Cloud has been shown to be a plausible source for these bodies (Kaib et al. 2009; Brasser et al. 2012). Thus, building a larger sample of these planet-crossing bodies may provide new constraints on the Oort Cloud, whose structure is intimately linked to the Sun's birth cluster and dynamical history (Brasser et al., 2006; Kaib et al. 2011).

1.5 SECONDARY SCIENCE GOALS

The CFHLS-VW and CFEPS experience proved that the work to acquire and exploit a data set like OSSOS is far beyond what a small team can handle. The secondary science goals for OSSOS will thus be handled by topic teams focussed on that project; space constraints prevent development of most of these cases; we will briefly motivate binary and occultation studies, and only mention other cases.

1.5.1 Binaries

Since the discovery of the first Kuiper Belt binaries (Veillet et al ww32) we know recognize that the Kuiper Belt is host to a large fraction of objects with binary companions, ranging from a few percent in the dynamically excited populations to upwards of 20-30% in the dynamically cold classical Kuiper Belt (Noll et al. 2008b). Like binaries elsewhere in astrophysics, the binaries in the Kuiper Belt provide a mechanism for probing the physical properties of these objects (Grundy et al. 2005, Noll et al. 2008a, Fraser & Brown 2010, Parker et al. 2011), as well as the dynamical environment of the current and primordial outer Solar System (Petit & Mousis 2004, Schlichting & Sari 2008, Parker & Kavelaars 2010, Nesvorny et al. 2011, Parker & Kavelaars 2012).

Kuiper Belt binaries are unique in the Solar System due to their wide separations, roughly equal-mass components, and similar colors (Benecchi et al. 2009). Using techniques like those presented in Lin et al. (2010), OSSOS observations will be directly sensitive to the widest of these binaries. Due to its excellent delivered IQ, CFHT has demonstrated that it is more effective at discovering these wide binaries than any other wide-field survey telescope currently in operation (of the wide binaries studied in Parker et al. 2011, three were found by the DES survey with the Mayall telescope, out of nearly 500 KBOs observed, while three were from the CFEPS survey with the CFHT telescope, out of less than 200 KBOs). Scaling the Parker et al. (2011) predictions to OSSOS, our observations will double the known population of the widest binaries. Drawing this relatively large sample of binaries from a single well-characterized survey will allow a more formal debiasing of the albedo distribution and other properties than previous samples, which were drawn piecemeal from several discovery surveys with poor characterization of discovery circumstances and other selection effects.

Another valuable aspect of the OSSOS survey from the binary perspective is the large resonant object sample. Binaries within resonant populations over a range of inclinations act as a diagnostic of the original source population for the now-resonant population; if resonant TNOs were captured out of the binary-rich low-inclination classical region, then a high fraction of binaries should have been carried along into the present-day resonant populations. However, if resonant TNOs were captured from a binary-depleted population like the classical TNOs now high inclination, there should be a low binary fraction in the present-day resonant populations. Thus a binary search in the resonant populations provides additional constraints on the cosmogony beyond the resonant-population ratios and consequently sheds further light on the migration of Neptune and origin of the Kuiper Belt (Murray-Clay & Schlichting 2011).

All identified wide binaries will be followed using ”potshot” style programs like those in Parker et al. (2011) at queue-scheduled facilities like Gemini to acquire a time-series of mutual astrometric measurements to determine mutual orbit properties. Additionally, a well-characterized sub-set of the OSSOS-discovered objects will be searched for more tightly-bound binaries to further confirm trends of binary fraction with primary object radius (eg., Nesvorny et al. 2011, Parker & Kavelaars 2012) which constrains the collisional history of the outer Solar System. This campaign will be carried out at a variety of facilities; successful campaigns have been run in the past using HST (eg., Noll et al. 2008b) and LGS AO to acquire high angular-resolution images in order to resolve TNO-binaries.

1.5.2 Occultations

The visual albedos of Kuiper belt objects are one of the most difficult observable parameters of these distant bodies. A few different methods have been developed to determine albedos, including resolved disk images of the largest few KBOs, and radiometry of many more. Despite the large observational hurdes, albedos, and hence diameters, have been determined for approximately 150 KBOs (Stansberry et al., 2008; Santos-Sans et al., 2012).

Some caveats arise with the use of these albedos, particularly for those determined by radiometry. Radiometric albedos are dependent on the thermal model used in calibrating the observed thermal fluxes. As well, the precision of the measurements is inherently flux limited, and as a result is biased towards the largest, hottest, and most proximate objects.

Stellar occultations by KBOs can provide a useful tool to infer the albedos of KBOs in an independent manner from other techniques, albeit with a different set of biases. The advantage with the use of stellar occultations rests in its measurement of cord length which provides a direct measurement of the section of the body which occulted the star. Like radiometry however, albedo determinations by occultation require certain assumptions about the body, including its shape, unless multiple cords are available to measure the objects projected surface area.

Current occultation efforts are highly pointed, focusing on a few particular KBOs until one or more occultations are detected. This is primarily a result of the substantial observing efforts required to predict when and where occultations will be visible. The OSSOS project represents the first opportunity to move occultation programs into the realm of large surveys. Two attributes of OSSOS are particularly important; the consistent survey nature of the program; and the self consistent internal astrometric calibrations of the program. The result of the program is 1000 tracked KBOs with ephemerides tied directly to the sources they might occult, minimizing the extra observations needed to make occultation predictions. In addition, the well understood detection biases of the program will provide a uniform sample from which the albedo distribution can be inferred in an unbiased fashion.

A dedicated team of observers has been assembled (due to space limitations only 4 are listed on the co-Is page) and are ready to take on the challenge of detecting occultations but objects in this sample, thus setting a new stage for KBO albedo determinations.

1.5.3 Other secondary goals

The OSSOS detections will be carefully inspected for *Cometary Activity* by analysis of their profiles, as especially some Centaurs are known to be active. (Jewitt (2009); Lorin & Rousselot, 2007) The *Surfaces* team will exploit the handful ($\sim$20) of new OSSOS detections bright enough to obtain spectra on 8-m class telescopes, and obtain high-quality (3% or better) colours in dynamical classes for which the colour cosmogny studies are interesting (Sheppard (2010); Romanishin et al 2010). For spectral observations, the *Thermal Models* team will match the species present on the surfaces with models of the formation and thermal evolution of the objects. The *Nearby* team will mine the OSSOS data for objects moving faster than the OSSOS rate cut (roughly inside of Saturn). The *Distant/Catalogs* team will analyse the OSSOS object catalogues for objects moving so slowly (hundreds of AU or further) that they are not detectable in our regular pipeline, such an object would be very large and this is an unlikely result whose importance is worth the effort; this team will also explore these catalogues for time-variable stellar phenomena that can be seen over the 5-month baseline, or even from year to year.

References

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2 Technical Justification

2.1 Context

The goal of the OSSOS program is to detect and track a sample of KBOs with a minimum of telescope resources while producing orbits precise enough to permit follow-up observations at 8-meter facilities in the following year and dynamical classification within 2 years of the initial observations. This time scale ensures rapid and timely exploitation of the discovery catalog to guide and constrain modelling of the formation of the outer solar system. Due to the slow physical motion of outer solar system bodies, achieving precise orbital parameters in 1 season of observing is not possible.
The desired sample size is describe in the Science Justification section and is required to allow selection between various competing scenarios the may describe the evolution of the outer solar system, detect new classes of objects and better define the known sub-structure (kernel and stirred components) of the Kuiper belt. This sample size and the desired diversity of heliocentric longitude (designed to probe librarian angles of resonant in the area of the sky where they come to peri-center) in sets the required area and pointing distribution. The single-exposure depth of the survey is a trade-off between avoiding trailing losses and image quality degradation (to ensure detectability of binary KBOs). For objects at 30 AU trailing losses / blurring become significant in exposures longer than about 6 minutes. The operational constraints of the telescope, however, determine that a program which requires in excess of 70 hours per semester at a single RA has a increased likelihood of failure. The need to rapidly determine the precise orbits of the KBOs with only a two year arc (to ensure the viability of the project) sets the required per semester cadence of the observations.

2.2 Field Locations and Exposure length

The principle targets of the OSSOS survey are the resonant KBO populations. The resonant KBOs are most detectable when they come to pericenter (due to the $r^{1/4}$ flux dependence for objects seen in reflected light). For this reason the OSSOS target fields are placed near the centres of the libration islands for objects in the 3:2 and 2:1 resonaces. Targeting the libration islands is a critically important efficiency for resonant detection. As the luminosity function is a steep power law, going deeper in a location where small objects are coming to peri-centre has a tremendous multiplier effect on the detection rate. In addition, survey at these peri-centre sweet-spots will enable us to probe the location of the knee in the size distribution of resonant KBOs, if that occurs at sizes larger than $H_r \sim 9$ (see Table 2.7). Two constraints work to set the exposure time. The exposure length must be kept short enough to minimize trailing losses while the area of sky observed in continuos blocks must be large enough to avoid losing objects due to orbit shear. In addition, operational constraints from the QSO process limit the length of a single observing sequence to 3 hours in length, as does the visibility of field blocks during observations 2 months before and after the field passes through opposition. Considering these various constraints we have settled on 287s (+40s overhead) exposures with 11 and 10 square degree blocks as providing an optimal trade-off between the competing constraints. These blocks (21 square degrees in total) will be arrange in 7x3 grids (see Figure 5) such a the fields are large enough to mitigate shear losses while small enough in RA extent to ensure easy QSO scheduling. The 11 degree blocks will require 3 hours to achieve a set of three observations, a detection triplet, which can be used to initially identify moving sources. A lower cadence at detection (2 exposures) results in a high number of false positives while more exposures in the sequence makes the blocks difficult to schedule and the extra exposure does not provide significant improvement in detection or orbit determination.

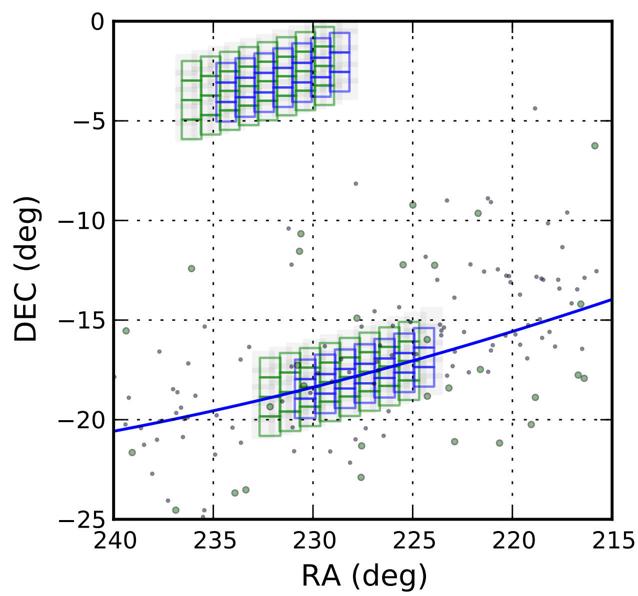

Fig. 5: Field layout (both on-ecliptic and off-ecliptic) for the 13A (blue) and 14A (green) semesters and the astrometric grid is shown in light grey. During the semester the fields will 'drift' to follow the retrograde motion of sources at $\sim$ 40AU. Green dots show the locations of known plutinos in the field while black dots represent the locations of other known trans-Neptunian objects.

2.3 Cadence

We have conducted modelling of the expected detection rate of sources under a variety of observing sequence and depths using the CFEPS Survey Simulator (Petit et al., 2011). We then model the tracking of this sample of objects by convolving our observing cadence with the observing efficiency that can be expected from CFHT QSO mode. Our anticipated per observation validation rate is based on the average validation rate per month derived from the CFHT MEGAPRIME statistics page. In addition, our simulated observing program considers the correlation between weather losses on subsequent nights, and even shows our strategy is robust to a week-long technical failure. These simulations provide a reasonable reproduction of our real-world experience at CFHT (CFEPS and the NGVS detection of KBOs). A joint Canada-France proposal executed in 2011B (44 hr) is serving as a testing ground for our cadence strategy and the above results are also in line with the performance from our 11B PI program. Despite 2011B being an extraordinarily poor semester this test program is achieving satisfactory completion.

The highly flexible CFHT QSO system plus MEGAPRIME is the only platform in the world capable of tracking a large orbital sample of TNOs. Other large format system on large aperture telescopes but operating in a non-queue mode can not achieve this program. The total integration time requested per lunation is a small fraction of the available above-horizon time (slightly less than PAndAS acquired each semester). All fields are above airmass 1.8 for +4 hours per night during our observing windows.

	Feb	Mar	Apr	May	Jun	Tot.
13A ecliptic field observations						
Discovery year grid is 7x3 fields						
cadence	3+1+1	1+1	1+3+1	1+1	1+1	16
exptime	9.53	3.82	9.53	3.82	3.82	30.5h
Ast. Gird: 11x5 fields, 60s/exposure, 3 dithers						2.8h
Shear/loss recovery time (per field)						1.7h
Total 13A ecliptic field Time						35h
Total 13A off-ecliptic field Time						35h
Total 13A time request						70h
14A ecliptic field observations						
Recovery year grid is 8x4 fields						
Cadence	3+1+1	1+1	1+1		1+1	11
time	14.53	5.81	5.81		5.81	32
area	8x4	8x4	8x4	8x4	8x4	24
Shear/loss recovery time (per field)						3h
Total 14A ecliptic field time						35h
Total 14A off-ecliptic field time						35h
Total 14A time request						70h

Tab. 1: Cadence/coverage/exposure time for 13A/14A. This table shows one quarter of the total OSSOS project. Derived from our simulations, we anticipate a validation rate of $\sim$ 65%, ($\sim$95% for A-class time and $\sim$45% for B-class time); this rate is slightly lower than that of NRC/CNRS programs in 11A ($\sim$67% overall, based on the QSO statistics) but higher than the 11A performance of NGVS ($\sim$ 52%). Our per-semester RA concentration is about 50% that of NGVS and thus our anticipated completion rate is closer to that of the NRC/CNRS values. All times include 40s/exposure overhead.

In each semester (A/B) we will observed one 'on ecliptic' and one 'off ecliptic' patch, each of 21 sq.deg. (Fig. 5). The first 2 years of OSSOS will thus be spent obtaining discovery and recovery observations of four of these patches. In years 3 and 4 a second set of four patches will have discovery and recovery observations conducted. Thus our program will require 2*35 70 hours in each of 13A,B and 15A,B for discovery and 70 hours in each of 14A,B and 16A,B for recovery. This includes a request an additional 3 hours in each 'recovery' semester to be used to chase down exceptional sources whose orbit shear may move them outside the recovery blocks and 1.7 hours to ensure loss of objects during the discovery phase is minimized. Thus, our total allocation request is 70 hours per semester for 8 semesters: 560 hours.

2.4 Observing Sequence

There will be four Discovery semesters and four Recovery semesters. We want to cover 42sq.deg., split into 21sq.deg. close to ecliptic, and 21sq.deg. at approximately 15deg off ecliptic. The off ecliptic / on ecliptic split is chosen to ensure a substantial fraction of sources detected (KBOs are more concentrated towards the ecliptic plan) while enhancing our sensitivity to KBOs with large inclinations (such objects spend a smaller fraction of their orbital period near the ecliptic plane and are cosmogonical important). Each of the 21 sq. deg. blocks will be further sub-divided into blocks of 10 and 11 pointings. During the 'triplet' observations each field of a block is observed in sequence and the sequence is repeated 3 times. Our 287s exposures + 40 seconds of overhead will require 327s per pointing, for the 11 pointing block this becomes 3600s per sequence or 3 hours per triplet. 3 hours is the limit of CFHT observing sequence, thus setting the maximum block size available for a triple of observations that are long enough to achieve our desired depth.

Each 21sq.deg. block is a patch of sky 7deg wide in RA and 3 deg wide in DEC (see Figure **??**) This field geometry ensures that as KBOs move on the sky they move within the patch of sky we are observing. This patch will be allowed to 'drift' during the semester to account for the bulk sky motion of the KBOs in the field.

During the Recovery semester we will expand the sky patches to 8x4 fields to account for object shear. An object with a semi-major axes of 30AU (inner edge of the Kuiper belt) will move 2.2 degrees in its orbit in a year whiles sources at 60AU, near the outer edge of our detection zone, will only move 0.8 degrees, thus expanding our patch by 0.5 degrees in all directions will help reduce loss near the boundary of our search grid. We also request an additional four hours of exposure time in each of the semesters in order to chase down any sources that have sheared beyond the sky patches. This time is particular important for chasing down sources discovered near the patch boundary. Near real-time search of the discovery triples (see Data Management section) ensures that we can follow-up shearing sources, even during the discovery semester.

2.5 Filter

The main goal of this project is to provide a well characterized set of Kuiper belt objects with well determined orbits as efficiently as possible. The wide-field of MEGAPRIME and the QSO scheduling of of CFHT make the ideal combination for detection and tracking of new sources. As KBOs are red, these observations are most efficiently performed in the r' band where the CFHT detectors have highly QE. Also, the r' band delivers superb IQ at CFHT with minimal IQ distortion from atmospheric dispersion in r', an important consideration for detection of binary sources.

2.6 Astrometric Precision

In addition to our basic search observation we will also conduct short observations on an 11x5 grid of pointings that overlaps, with some buffer, the search/recovery field grid. These 'astrometric' observations will be used to create an astrometric catalog to tie together the plate solutions from each of program observations. We have found that such an astrometric grid reduces the 'internal' astrometric error by a factor of between 5 and 8 (Gwyn, 2008). This improved internal precision enables more rapid orbit determination (with few total observations) and is a key component of our observing strategy. We have constructed such a grid for our pilot program running in 11A which is providing residuals of 0.030" when fitting orbits as compared to 0.25" residuals typically seen in our CFHT-LS project.

2.7 Number of objects expected.

Using the CFEPS survey simulator with the CFEPS L7-model, including the full classical belt (inner, main, outer) and the resonances for which we have population estimates we have determined the expected rates of detection of the OSSOS project, based on the cadence, depth and field locations described above (see table 2.7).

The faint end is not precise due to uncertainties on the H distribution slopes, but should be ok for brighter limits.

Population	large-Knee	small-Knee
Inner		
Main		
3:2		
2:1		
5:2		
Other Resonces		
Outer		
Scattering		
Total		

Tab. 2: Expected detection rates based on the CFEPS L7 model and flux/area coverage describe here. The 'large-Knee' column describes our expected detection rate if their is a knee is the Size-Frequency Distribution (SFD) (where the distribution transition from steep to flat) near $H_r \sim 8.5$ (Fuentes et al. (2009),Fraser & Kavelaars (2009)) where as the small-Knee column lists the expected detection rate if that transition occurs at $H_r \sim 10.1$ which is more consistent with the transition observed in the asteroid belt. **NUMBERS FINALIZED ON TUESDAY MORNING**

2.8 Other Facilities

2.8.1 Subaru and Hyper-Suprime-Camera

The HSC Solar System science collaboration (PI: F. Yoshida, with W. Ip and P. Lykawaka of that collaboration also OSSOS for the dynamical aspects) proposed obtaining 5-colour photometry (Yoshida et al., 2011), but has learned that the HSC-Survey will not be time sequenced in a way that orbits could be obtained, and getting a large orbit sample would require more time than is available in P.I. proposals. We are thus negotiating collaboration in which the HSC Solar System team would propose for PI mode time and acquire data on some of the OSSOS sky patches. Although colour data on the bulk of the sample is not crucial for OSSOS primary science goals, accurate (few percent) colours on a large sample of $m_r \sim 25$ TNOs would only be possible with HSC, and thus this would be a useful complement to the more targeted OSSOS colour work by the Surfaces team.

2.8.2 LSST

The LSST project may come online a decade from now. The latest timeline (see LSST.org) would have an operational phase beginning only in 2022 (if there are no further slippages). The outer Solar System science projects a limit of about 24.5 (slightly shallower than OSSOS) over a large area.

We do not feel that such a distant project (which, with the current funding situation may suffer further significant delays) should be used to argue that Solar System science should wait a decade or more before progress, and then to be done by another community (the logical conclusion would be to dismantle Megaprime immediately). Signficiant progress can be made, led by the CFT communities, in the near future using the power of CFHT+QSO.

3 Data management

The core data analysis team (Gladman, Kavelaars and Petit) will search of moving sources as the data is acquired each semester. This team has extensive experience working with CFHT on the delivery and processing of observations for Kuiper belt research. During the CFHTLS-VW project an extensive detection and tracking pipeline, which has since undergone continuos improvement, was developed. This pipeline, combined with software techniques developed for difference imaging, which have been successfully added to the CFEPS pipeline and used in the detection of KBOs in the NGVS CFHT-LP, will be used to detect moving sources a few days after the data arrive in the CADC archive.
Data processing will occur in three phases.

- Quick Look Process will be done as data arrive in the CADC archive. This processing is based on the 'RAW' MEGAPRIME data, flattened and debiased by team produced software. This initial pass through the data enables the rapid detection of moving sources. This rapid detections allows dedicated follow-up observations to be scheduled if sources are found to moving off the survey sky patches.

- End of Lunation Processing: at the end of each lunation CFHT supplied 'ELIXER' pre-processed files which will be run through the CFEPS pipeline. This process provides improved astrometry and photometry, compared to the 'Quick Look' processing. These end of lunation observations are used to build up the tracking of detected sources. This detection catalog will then be distributed to the team members to enable planning for followup multi-wavelength observations at other facilities (VLT, GEMINI, KECK, MAGELLAN and Subaru).

- End of semester processing: at the end of each semester all the data from a given block is processed through the MEGAPIPE astrometric pipeline. This pipeline ties the astrometric solution of each frame to a common reference grid. These common tied frames are then used to form a template and a re-search of the OSSOS observations, using a differencing approach, will be conducted. This final search will form the high-precession, high-sensitivity catalog that will be used by the CFEPS Survey Simulator.

3.1 Data Publication

As with the CFEPS project, the team will provide a Survey Simulator and characterization file that will enable theorist to compare models of the formation of the outer solar system to the detections from this survey. The Survey Simulator enables modellers to see the effects of 'Non-detections'. For example, if the Simulator demonstrates that a given model would produce detections that are not seen in the observation catalog, then that model can be ruled out. Such 'non-detection' constraint is only possible when a complete modelling of the observational survey is available. The CFEPS catalog and Simulator have been very powerful in this respect.

3.2 Publication

The OSSOS team consists of 45+ observational astronomers and modellers interested in various aspects of the OSSOS catalog detections. This array of scientist is primed to take full advantage of this new and unique resources for solar system research. The core OSSOS team (the data analysis team and the topic team leads) will meet via bi-weekly teleconference to discuss the progress of the survey observations and data exploitation. In addition, the OSSOS project will meet once per year, nominally in parallel with other science meetings taking place. The OSSOS team anticipates having our first 'All Hands' meeting at the Division of Planetary Science meeting in October 2012.
The detection catalog from OSSOS will be published to the Minor Planet Centre (MPC) 6 months after the conclusion of the 'recovery' observation semester.

4 Target RA distribution

A Semesters, 2013-2016

RA	Hours
00-04	0
04-08	0
08-12	0
12-16	70
16-20	0
20-24	0

B Semesters, 2013-2016

RA	Hours
00-04	70
04-08	0
08-12	0
12-16	0
16-20	0
20-24	0

Tab. 3: Note that the chosen fields will be visible for 5 dark runs centered on the opposition month.