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

Title:	OSSOS: the Outer Solar System Origins 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 an object sample along with a calibrated Survey Simulator that will make this survey vastly more powerful at model descrimination than existing data sets, allowing 'precision Solar System science'. 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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Co-Is (Name, Institute)	See Attached list on following page.

Total number of **hours** requested: 560

Hours per agency:	Canada 252	France 252	Hawaii 0	Brazil 0	China 0	Taiwan 56

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 participating-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 have left many basic questions unanswered. In fact, obserservations have repeatedly revealed totally unexpected new classes of objects not yet appearing in models and thus generated 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 concerted effort to acquire a new well-understood TNO sample focussed on the most cosmogonically-important subpopulations, 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 [1, 2, 3, 4]. 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 [5], 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 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)** [59], which, although producing solid science contributions to Kuiper Belt science, [6, 7, 8] discovered and tracked only 169 TNOs instead of the 1300-object goal of CFHLS-VW. The experience gained along the way shows that this type of survey *is* the future of Kuiper Belt science as the only way to quantitatively test models. The majority of previous survey work was both insufficiently calibrated and tracked haphazardly so that it is impossible to interpret the orbital distributuion of the ∼800 multi-opposition TNOs [5]. The OSSOS survey is thus intended to finally be the Kuiper Belt survey this science 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 general astronomical surveys not optimized for outer Solar System cadence will lose the majority of their objects and not meaningfully multiply the current orbital database, thus having 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

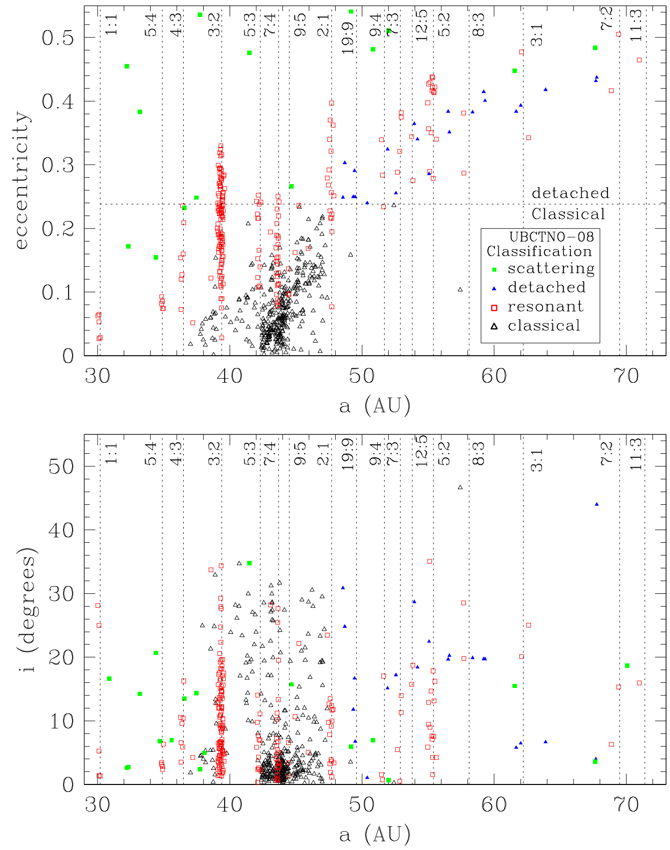

Fig. 1: Orbital element diagram for the a=29–73 AU Kuiper Belt, showing the rich dynamical structure needing to be cosmogonically explained. Top: a/e structure with resonant TNOs in red. Centaurs are scattering objects to the left of this figure, while the detached, scattering, and resonant populations continue off the upper right at larger a and e. Bottom: The a/i structure, with some extreme-inclination objects ($i > 50°$) off the top of this plot.

Belt, but because the Kuiper belt quickly became more complex, 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* $a <$ 30AU 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 [9].

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, [10, 11, 12])? Or were they trapped into the resonances out of a scattering population and then had their e's cycle down (proposed in the context of the 'Nice model' [**?**])?
2: In the latter case, the entire hot population was dramatically transplanted 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 other properties (eg. size distributions) of these populations?
3: Are the scattering TNOs simply a decaying remnant of a huge primordial population emplaced during giant-planet 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 [52] 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 TNOs get their perihelia raised? Some [15]suggest that these are objects which were temporarily resonant, but during planet migration they were dropped off. Others hypothesize [16, 17, 18] 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, [19]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 ~500 AU, never approaches the Sun closer that 75 AU; some [20]view this as an object related to the Oort cloud while others consider it an extreme detached TNO. Objects on $i > 50°$ scattering orbits, or even retrograde orbits like Drac [21]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 the exposures via QSO virtually guarantees one's ability to acquire a large sample of high-precision orbits (even with bad weather, see Tech section). Although CFHT+Megprime's depth×FOV is 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 (~ 20□°) 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 detections 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 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 precise statements about orbital structure that CFEPS and its Survey Simulator were able to. Without such exceedingly well-calibrated surveys, rigorous quantitative tests of planet-formation models cannot be made.
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. Simplifying somewhat, the dynamics of a mean-motion resonance are encoded in the resonant angle $\phi_{jk} = j\lambda - k\lambda_N - (j-k)\varpi$ where ϖ is the perihelion longitude of the TNO (roughly, along the ecliptic), $\lambda = \mathcal{M} + \varpi$ is its angular position along the orbit with $\mathcal{M}$ being the mean anomaly measured from perihelion, and λ_N is the same quantity for

Neptune. Using the important 3:2 resonance as an example, the time derivative of 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 (*eg* 60° for Neptune Trojans, 60–100° for 2:1 resonators). The resonant angle's libration then confines the on-sky locations of perihelion relative to Neptune to a restricted set of longitudes within $(A_\phi/k)^\circ$ of the libration center offset longitude. This introduces devilishly-complex biases into the detection process [8], which only a well-characterized survey can take out. The Technical section explains how this influences the OSSOS field choice).

For example, the 3:2 librators (visible in Fig. 1.1) 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 [22] 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 CFEPS survey pointing history and flux biases (as the only sample for which this can be done quantitatively), agrees for the distribution of e and detection distance, but not for the i (Fig. 2) 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 in this model. Such detailed model rejection is only recently possible in Kuiper Belt science, and OSSOS will continue in this vein.

The size distribution of the 3:2 resonators is accessible via their absolute magnitudes H, obtainable once the orbits are known. Because they approach the Sun closely, the 3:2 resonance detections will probe diameters below the 50-km radius, which is near the diameter where models [57, 58] and observations [29, 55] suggest a transition to a shallower slope in the size distribution should occur. This is easier to see in the plutino population than the more distant classical belt. OSSOS will have sufficient number of detections in this resonance (see Table 1 in Tech. Just.) that such a roll-over will be reliably detectable. Only in the scattering population could such a roll-over also be detected, but with vastly fewer statistics.

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. The processes identified are then candidates for operation in the wide vareity of debris disks While there are a huge number of questions that can be posed, we concentrate on a few major ones that OSSOS will address.

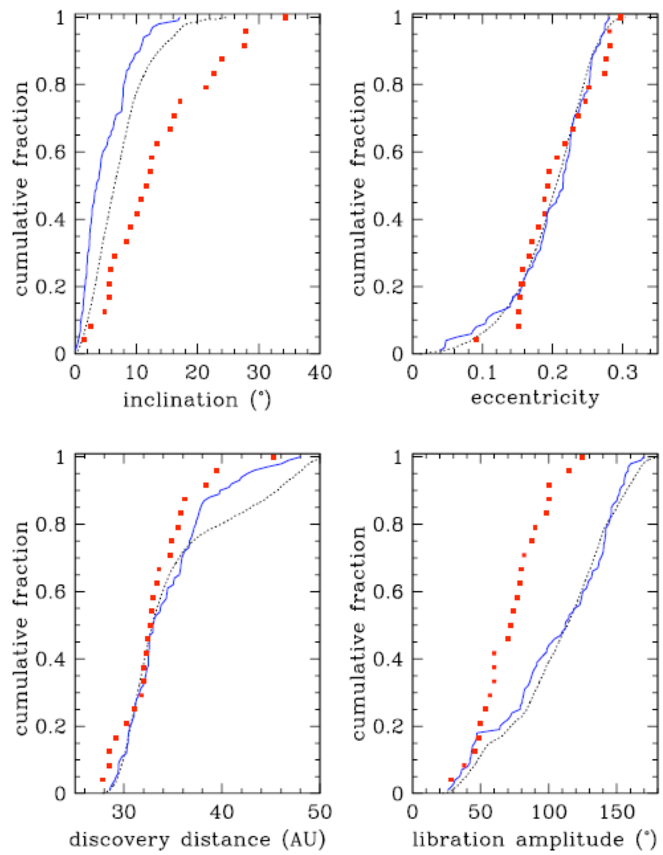

Fig. 2: Comparison of the results of a Nice-model simulation's orbital distribution of 3:2 resonators (curves) to the Canada-France-Ecliptic Plane Survey's (CFEPS) detections (red squares), for 4 orbital parameters. In each case the dotted black curve shows the model's cumulative distribution of that 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.

Resonant population ratios There is already known occupancy in resonances ranging from the 1:1 (Neptune Trojans) at 30 AU out to 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, like those discussed in Question 1. For example, the 2:1 and 5:2 are other resonances (see Fig. 1.1) which efficiently trap (like the 3:2) large numbers of TNOs. In one model of smooth outward migration [12] the population ratio expected in the 3:2/2:1/5:2 resonance trio is 2/5/1 respectively, due to the great efficiency of 2:1 trapping. In models like the Nice model [14]the closer resonances are favoured, giving a ratio of 8/3/1. CFEPS [8]debiases the detections to a true ratio pattern of 4/1/4, which agrees with neither of these models because it reveals that 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 flux-limited sample is expected to be in these resonances and tracking biases against their eventual identification are severe [5]. Even with this, the few objects known indicate [8]that the population in distant 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.

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 [23]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 differ in the fraction of all 2:1 TNOs that are in the large-A_ϕ (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 [24, 8]

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 $\sim$ 40 2:1 resonantors detected by OSSOS, even if half were symmetric resonators, a positve measurement of non-equal populations (and thus detection of ancient planet migration) will be possible. Essentially measuring leading/trailing ratio of the 2:1 would confirm for the first time that planet-migration happened, while the symmetric to asymmetric ratio (Fig. 3) is diagnostic of how far and how fast Neptune moved.

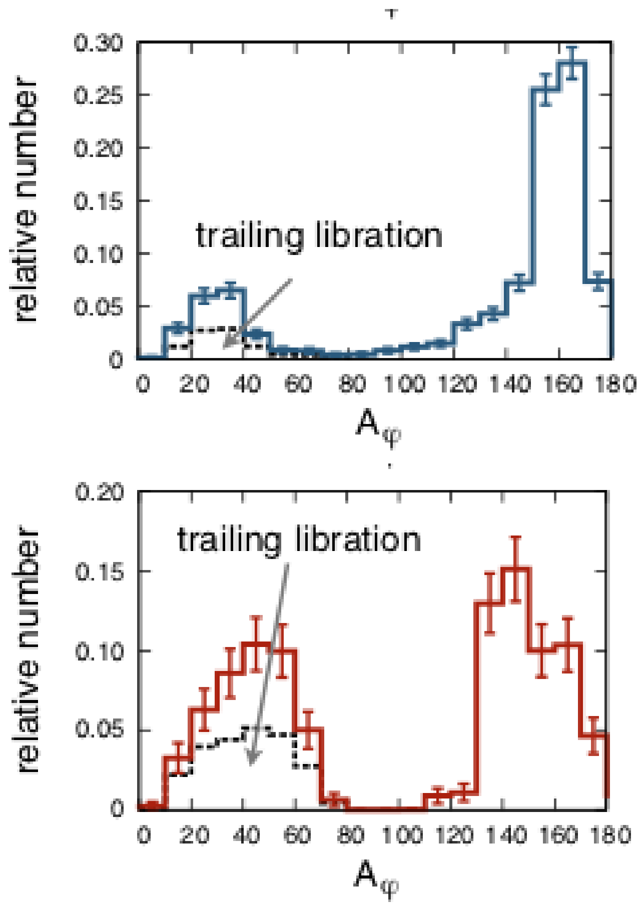

Fig. 3: 2:1 libration amplitude distributions from a 7-AU smooth migration into a pre-existing Kuiper Belt (top) or a short (2-AU) migration into a scattering population (bottom) which traps 2:1 resonantors. Amplitudes $A_\phi > 80°$ are symmetric librators, while smaller A_ϕ means asymmetric libration with the dotted histogram applying to the smaller trailing librator population. Because these are both migration models, an asymmetry in asymmetric librators is produced, but the models have different fractions of symmetric librators (roughly 50% vs 85%).

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 [7]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. A concentration of orbits in the a=43±1 AU region at low-e and i was initially postulated to be a large collisional family [25]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 [26, 27]). 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 important constraint for theories, which must leave this structure intact while simultaneously implanting the resonant and scattering populations.

The Scattering population OSSOS should detect $\sim$ 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; uncertainties 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 [28, 14], 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 Fig. 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. The detached objects (with perihelia high enough that they are not scattering today) serve as an additional constraint on these models; such theories can only be constrained with a well-calibrated survey with complete tracking because the detection and tracking biases against such objects are strong.

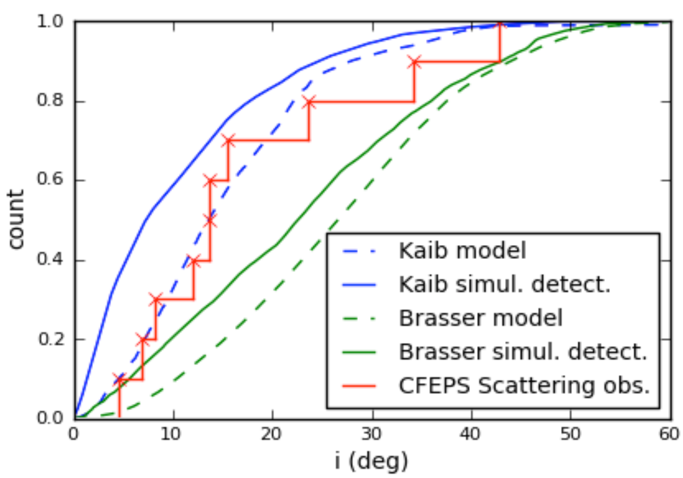

Fig. 4: The inclination distribution depends on whether the scattering population was generated by simple scattering of the planets in their current locations (updated by Kaib et al 2012 similar to [28])or having the giant planets pass through an early dynamical instability like the 'Nice model' (Brasser 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 simullator, would results in the detected samples (solid curves) being concentrated to smaller i. The small CFEPS scattering 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.

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 [29, 7] 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 [30, 31]. 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 [21, 32], and although the Oort Cloud has been shown to be a plausible source for these bodies [33, 32] a complete model still lacks enough detections to be tested. 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 [17, 34].

Expecting the Unexpected Nearly every single large survey has discovered TNOs with orbital properties that were totally unexpected. Resonant TNOs, scattering objects, detached objects, and those with extreme inclinations all qualified at the time. By more than doubling the number of high-quality orbits known, we feel confident that OSSOS will again reveal zero-order science questions; this is not a field that is refining the details of parameter space, but still regularly uncovers the unexpected.

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.

Binaries Since the discovery of the first Kuiper Belt binaries [35]we now 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 [36].Like binaries elsewhere in astrophysics, the binaries in the Kuiper Belt provide a mechanism for probing the physical properties of these objects [37, 38, 39, 40], as well as the dynamical environment of the current and primordial outer Solar System [41, 42, 43, 44, 45].

Kuiper Belt binaries are unique in the Solar System due to their wide separations, roughly equal-mass components, and similar colors [46].Using techniques like those presented in [47],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 [40],three were found by the DES survey with the Mayall telescope, out of nearly 500 TNOs observed, while three were from the CFEPS survey with the CFHT telescope, out of less than 200 TNOs). Scaling the Parker et al. [40] 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 that now in the hot classical belt, 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 [48].

All identified wide binaries will be followed using ”potshot” style programs like those in [40] 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., [44, 45]) 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., [36]) and LGS AO to acquire high angular-resolution images in order to resolve TNO-binaries.

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 TNOs, and radiometry of many more. Despite the large observational hurdles, albedos, and hence diameters, have been determined for approximately 150 TNOs [49].

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 TNOs can provide a useful tool to infer the albedos of TNOs 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 TNOs 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 TNOs 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 by objects in this sample, thus setting a new stage for KBO albedo determinations.

Other secondary goals The OSSOS detections will be carefully inspected for *Comet-ary Activity* by analysis of their profiles, as especially some Centaurs are known to be active [50, 51]. 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 [52, 53] 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. The Lightcurves team will lead a statistical study of the rotation rates and amplitudes of TNOs and will make follow up measurements on objects that suggest unique properties (large amplitude, rapid rotation) to better understand collision properties in the Kuiper Belt.

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Population	100-km knee	No knee
Inner	18	24
Main	906	918
3:2	194	266
2:1	34	36
5:2	56	64
Other Resonances	110	124
Outer	72	84
Scattering	26	54
Total	1416	1570

Tab. 1: Expected detection rates based on the CFEPS L7 model and flux/area coverage described here. The '100-km 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 100-km diamaeter [55, 29] everywhere in the belt. The no-knee column lists the expected detection rate if there is no such transition. The difference is most easily detected in the 3:2 resonator population.

2 Technical Justification

2.1 Context/Summary

The goal of the OSSOS program is to detect and track a sample of TNOs 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.

Using the CFEPS survey simulator with the CFEPS L7-model [7, 60], 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 below (see Table 1).

The science described in the Science Justification section requires a sample of >1000 TNOs to allow descrimination between various competing scenarios that 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 main Kuiper belt. This sample size and the desired diversity of heliocentric longitude (designed to probe libration angles of resonant in the area of the sky where they come to peri-center, see Figure 5) 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 TNOs). 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 TNOs with only a two sequential data semesters (to ensure the viability of the project) sets the required per semester cadence of the observations.

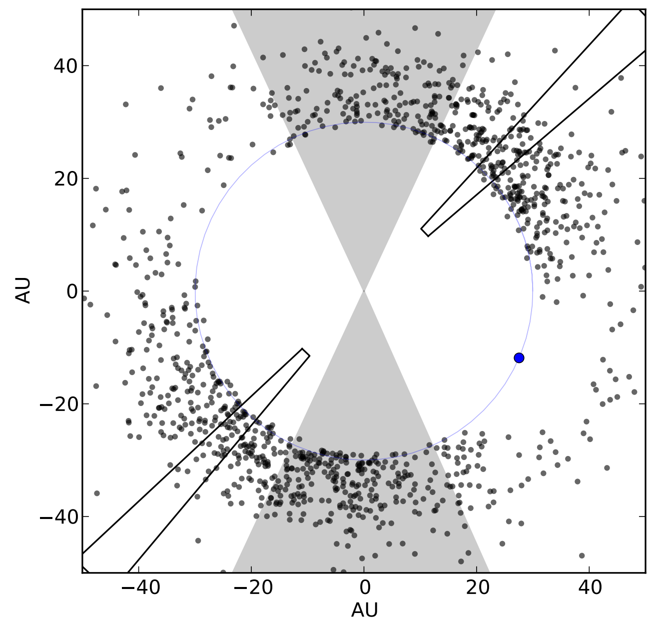

Fig. 5: A top down view of the outer solar system. Black dots indicate the May 2013 locations of all 2:1 resonant objects brighter than our flux limit, from the CFEPS-L7 resonant model [8]. The black-lined boxes show our on-ecliptic observing windows during the 13A/B discovery observations; different longitudes will be used in 2015 A/B. Grey wedges indicate unusable regions due to stellar crowding in the galactic plane. The blue dot indicates Neptune's location. This view shows the strong preference for observing at particular sky longitudes, maximizing resonant-TNO detection in a flux limited sample. Only the 2:1 resonant sources are shown (for clarity) but analagous preferences exists for all resonant populations as they avoid perihelia near Neptune.

2.2 Field Locations, Exposure length and Observing cadence

The principle targets of the OSSOS survey are the resonant TNO populations. TNOs 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 n:2 and n:1 resonances (Fig. 5). Targeting the libration islands correctly is critically-important for resonant detection. As the luminosity function is a steep power law, going deeper in a location where small objects are coming to perihelion has a tremendous multiplier effect on the detection rate. In addition, observing at these pericentre sweet-spots enables OSSOS to probe the location of the knee in the size distribution of resonant TNOs, if that occurs at a TNO radius > 50 km (see Table 1).

Two constraints work to limit the exposure time and set size of our sky patches. The exposure length must be kept short enough to minimize trailing losses. 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. Simultaneously, the area of sky observed in continuous blocks must be large enough to avoid losing objects due to orbit shear.

For our detection process we require 3 sequential exposure (separated by roughly 1 hour duration) to enable the detection of moving sources, we refers to these 3 exposures as detection 'triplets'. To ensure peak detection efficiency, two sets of triplets (6 exposures total) should be acquired during the discovery semester. Neither of those sets can be acquired in the month before or after a given field passes through opposition as at those solar-elongation there is considerable confusion from objects in the asteroid belt. In our survey design we acquire the first triplet 2 months before opposition and then the second triplet at opposition. If one of those triplets is unsuccessful, a third window (two months after opposition) can be used to acquire a second triplet.

Considering all constraints, we settled on 287s (+40s overhead) exposures with 11 and 10 sq. deg. 3-hr OGs as providing an optimal trade-off between the competing constraints. These two OGs create a contiguous 21 square degree block in a 7x3 grids (see Fig. 6); such blocks are large enough to mitigate shear losses while small enough in RA extent to ensure easy QSO scheduling. The 11-field OG will require 3 hrs to acquire a triplet; the 10-field OG 10% less. A poor 2-exposure cadence at detection 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.

Tracking observations. To enable precise orbit determination we must also acquire a sampling of the sky positions of the newly discovered TNOs, at a variety of solar elongations. These observations are in-addition to the discovery triplets.

We have modelled the expected TNO detection rate under a variety of candidate OSSOS observing sequences and depths using the CFEPS Survey Simulator. 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

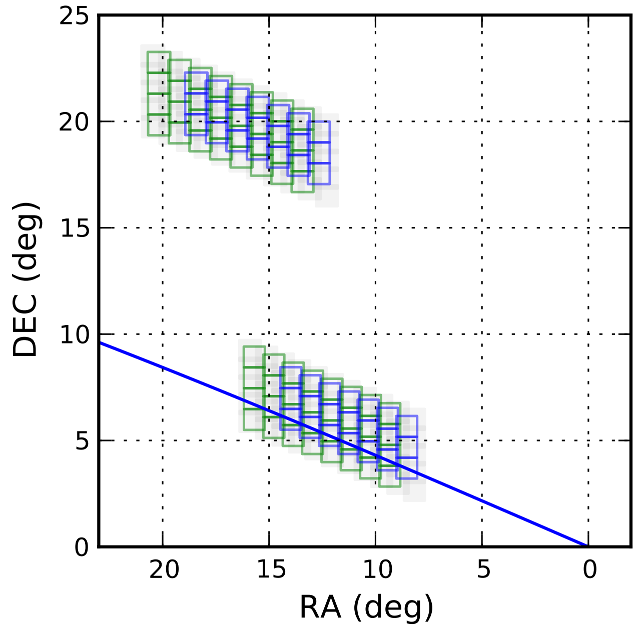

Fig. 6: Field layout (both on-ecliptic and off-ecliptic, 21 sq. deg. each) for the 13A (blue) and 14A (green) semesters and the astrometric grid is shown in light grey. During the semester the fields 'drift' to follow the retrograde motion of sources at ~ 40AU, and then jump back west in the second year.

CFHT (CFEPS and the NGVS detection of TNOs). 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 this 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 cannot achieve this observation cadence. The total integration time requested per lunation is a small fraction of the available above-horizon time, and slightly less than PAndAS acquired each semester. All fields are above airmass 1.8 for +4 hours per night during our observing windows.

In each semester (A/B) we will observed one 'on ecliptic' and one 'off ecliptic' patch, each of 21 sq.deg. (Fig. 6). 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 (see Table 4). This includes a request for 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 as rapid movers near the edge of our discovery grid

will shear off the discovery patch. Thus, **our total allocation request is 70 hours per semester for 8 semesters: 560hours.**
A+B Band. As part of the CFHT-LP process each program is treated as an agency and must divide its exposures between A-band (95% completion) and B-band. During the 13A/B and 15A/B 'discovery' semesters the two sets of triplets plus one single night observation following closely after the initial triplet (26.7 hours or 38% of the observing time request in our discovery years) comprise our 'A' band program. During our 'recovery' year the triplet plus 1 of the 'tracking observations' (see Table 2) as well as the 3 hours of exposures to chase-down objects that sheared off the grid in the 2nd year are considered the 'A' program (29.2 hours or 41% of the observing time requested during our recovery years). The Astrometric grid and other tracking observations will be programmed in 'B' time. This division between A and B time is taken into account during our cadence simulations.

2.3 Observing Patches

During the 'discovery' years (13A/B, 15A/B) each 21 sq.deg. patch is 7deg x 3deg in size (Figure 6). This field geometry ensures that as TNOs move on the sky they remain within the patch of sky we are observing. This patch will 'drift' during the semester to account for the bulk sky motion of the TNOs in the field, reducing shear losses.
During the Recovery semester we will expand the sky patches to 8x4 fields to account for orbit shear moving east to to larger RA to account for annual orbital motion. Object's with a semi-major axes of 30AU (inner edge of the Kuiper belt) will move 2.2 degrees in a year whiles sources at 60AU, near the outer edge of our detection zone, only move 0.8 degrees, thus expanding our patch by 0.5 degrees in width and height will help reduce loss near the boundary of our search grid. We also request additional time (see Table 4) 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, where losses are biased towards the important scattering objects which are often nearby and rapidly moving.

2.4 Filter

OSSOS will 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 CFHT make the ideal combination for detection and tracking of new sources. As TNOs are neutral to red, these observations are most efficiently performed in the r' band where the CFHT detectors have high QE. Also, the r' band delivers the best IQ distribution at CFHT, an important consideration for detection of binary sources, with minimal IQ distortion from atmospheric dispersion in r' which is important as our tracking fields off opposition will often be taken at AM>1.3 and r' maintains its image quality better as one drops to the horizon.

2.5 Astrometric Precision

We will acquire short observations on an 11x5 grid of pointings that overlaps, with some buffer, the search/recovery field grid (see Figure 6). These 'astrometric' observations will be used to create an astrometric catalog to tie together the plate solutions of each observation. Such an astrometric grid reduces the 'internal' astrometric error by a factor of between 5 and 8 [54], enablelling more rapid orbit determination (with fewer total observations) and is a key component of our observing strategy. We have constructed such a grid for our pilot program running in 11B which is providing residuals of 0.03" when fitting orbits as compared to 0.25" residuals typically seen in our CFHT-LS project.

2.6 Other Facilities

Subaru and Hyper-Suprime-Camera (HSC). The HSC Solar System science collaboration (PI: F. Yoshida, with W. Ip and P. Lykawaka of that collaboration also OSSOS members for the dynamical science) proposed obtaining 5-colour photometry [56], but has now learned that the huge HSC-Survey will not be time sequenced in a way that orbits could be obtained (and will instead be optimised entirely for extra-galactic and cosmological science). Getting a large HSC orbit sample would require many times more allocation than is available in P.I. proposals. We are thus negotiating a collaboration in which the HSC Solar System team, in cooperation with ourselves and our Princeton co-I's) would propose for PI mode time to acquire photometric data on one of the OSSOS sky patches ($\sim$ 20 hr of HSC time). Although colour data on the bulk of the sample is not crucial for OSSOS primary science goals, accurate (few %) colours on a sample of $\simeq 300\ m_r \sim 25$ TNOs (only possible with HSC) would be a useful complement to the more targeted OSSOS colour work by the Surfaces team.
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. The core team will be supplemented (not listed) by a future postdoc and several PhD students whose theses will be based upon this superb data set. 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 continuous improvement, was developed. This pipe-line, combined with software techniques developed for difference imaging, which have been successfully added to the CFEPS pipeline and used in the detection of TNOs 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 Agency Shares

This CFHT Large Program will require 560 hours of Megaprime time to complete. We have elected to divide the time between the three participant agencies in roughly equal proportion to their current number of nights at CFHT, i.e. 10%/45%/45% for Taiwan/Canada/France. This distribution results in our per-semester request (70 hours) being divided as 7 hours from Taiwan and 31.5 hours from each of Canada and France.

3.2 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.

3.3 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 'discovery' observation semester (about 11 months after the first data is taken on that block).

4 Target RA distribution

Although in any given semester, this is essentially a single-RA program, the amount of time in any given dark run is small. The table below breaks down the monthly timing for the on- and off-ecliptic fields for the A semesters 2013 and 2014.

	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 patch)						1.7h
Total 13A ecliptic patch Time						35h
Total 13A off-ecliptic patch 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
Shear/loss recovery time (per patch)						3h
Total 14A ecliptic patch time						35h
Total 14A off-ecliptic patch time						35h
Total 14A time request						70h

Tab. 2: 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 ∼ 65%, (∼95% for A-class time and ∼45% for B-class time); this rate is slightly lower than that of NRC/CNRS programs in 11A (∼67% overall, based on the QSO statistics) but higher than the 11A performance of NGVS (∼ 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.

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.