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C. R. Physique 4 (2003) 743–753

COMPTES RENDUS PHYSIQUE

New frontiers in the Solar System: trans-Neptunian objects/Les nouvelles frontières du système solaire : les objets transneptuniens

Discovering and securing TNOs: the CFHTLS Ecliptic survey

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Presented by Pierre Encrenaz

Abstract

We have developed an international collaboration aimed at discovering and long-term tracking of a large Trans-Neptunian Object (TNO) sample. The scientific rationale behind this extended observational effort is to understand the dynamical structure of the outer Solar System. This structure provides a unique tracer of planetary accretion processes and constrains models of formation and early evolution of our outer Solar System.

Our observational program is designed to first discover a large sample of TNOs in well characterized surveys and then track them in a manner which will avoid what we call 'follow-up bias'.

We first briefly describe the current status of our current observational knowledge of the Kuiper Belt. Next we show how following-up almost all objects discovered in a survey has changed our view of the dynamical structure of the Kuiper Belt. Thanks to our work, previously empty places have been filled in, the relative importance of the then known dynamical population have been largely modified, and a new, potentially very large, population have been discovered. Discoveries presented in this paper were done at CFHT, while recoveries were performed on multiple telescopes, including in particular the ESO telescopes and the MPIA telescopes in Calar Alto (Spain).

Finally, we briefly describe the ecliptic component of the CFHT Legacy Survey for which Kuiper Belt science is the main driver. Our experience with discovery and follow-up observations has led us to design an efficient time-sequence of observations for this survey. ***To cite this article: J.-M. Petit, B. Gladman, C. R. Physique 4 (2003).***

Résumé

Découvrir et suivre les OTN : le Grand Relevé Ecliptique du CFHTLS. Nous avons développé une collaboration internationale dans le but de découvrir et suivre sur le long terme un grand nombre d'Objets Trans-Neptuniens (OTN). Le but scientifique qui soutend cet effort observationnel intensif est la compréhension de la structure dynamique du Système Solaire externe. Cette structure est un marqueur unique des processus d'accrétion planétaire et permet de contraindre les modèles de formation et d'évolution primordiale du Système Solaire externe.

Notre programme observationnel est prévu pour découvrir un grand échantillon d'OTN dans des relevés bien caractérisés et de les suivre de manière à éviter les « biais de suivi ».

Nous décrivons d'abord l'état actuel de notre connaissance observationnelle de la ceinture de Kuiper. Ensuite nous montrons comment le suivi de tous les objets découverts dans un relevé a changé notre vue de sa structure dynamique. Grâce à notre travail, des régions vides jusqu'alors ont pu être peuplées, l'importance relative des différentes populations connues a été grandement modifiée, et une population nouvelle, potentiellement très importante, a été découverte. Les découvertes présentées dans cet article ont été réalisées au CFHT, et le suivi s'est fait sur de nombreux télescopes, en particulier ceux de l'ESO au Chili et ceux du MPIA à Calar Alto (Espagne).

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1631-0705/$ – see front matter
doi:10.1016/j.crhy.2003.10.004

Finalement nous décrivons succintement la composante écliptique du grand relevé CFHT Legacy Survey pour laquelle l'étude de la ceinture de Kuiper est la justification scientifique principale. Notre expérience dans les observations de découverte et de suivi nous a permis de définir une séquence temporelle efficace pour les observations de ce relevé. ***Pour citer cet article : J.-M. Petit, B. Gladman, C. R. Physique 4 (2003).***

Keywords: Kuiper Belt; Trans-Neptunian objects; Discovery

Mots-clés : Ceinture de Kuiper ; Objets trans-neptuniens ; Découverts

1. Introduction

Roughly 100 planets around other stars have been discovered in the past few years. Due to detection biases all these planetary systems are dominated by the presence of a large gas giant (jovian) planet or planets. These discoveries have had the benefit of motivating closer investigation of the formation of our Solar System's gas giant planets (Jupiter, Saturn, Uranus and Neptune). The formation of our planetary system Sun was a complex process with ill-understood details. Questions as basic as the location of planet formation and their formation mode (single-phase collapse or agglomeration) remain unanswered. In addition, understanding the formation of the giant planets by studying their current properties is complicated by the fact that they are now physically and chemically evolved [1].

Extensive surveys of the asteroid belt have been used to map its dynamical structure and explore the details of the inner solar system's orbital dynamics. The measured dynamics have, in turn, stimulated detailed numerical modeling of the inner solar system and allowed the dynamical history of the region to be examined. Links between asteroid spectral types and meteoritic studies have provided information on the composition and physical conditions of the proto-planetary nebula. Studies of the asteroid belt have also been crucial for understanding the histories of the terrestrial planets. For example, the study of meteorites (strongly linked to the main asteroid belt) has yielded abundant information on the physical conditions in the proto-solar nebulae in the 2–4 AU range. The asteroidal orbit distribution has been sculpted by gravitational interactions with the planets over the lifetime of the Solar System [2] and, during the more violent period of our Solar System's formation, by larger bodies passing through it [3].

For the outer Solar System the lack of small body belts exterior to Jupiter meant that similar studies were not possible for the giant planets. Kuiper [4] suggested the existence of a belt of material in orbits with semi-major axis between 30 and 50 AU, based on the observed distribution of short period comet orbits. Gladman and Duncan [5] and Holman and Wisdom [6] showed that after the giant planets reached their current masses the regions between them would be emptied of planetesimals on time scales much smaller than the age of the solar system. However, these studies also showed that outside of Neptune the hypothesized 'Kuiper Belt' was stable, supporting modelling of Duncan et al. [7] that the short-period comets come from this source via long-term gravitational instability. The general picture developed from these studies was that of a dynamically cold Kuiper belt outside Neptune, representing a leftover fossil of the planetesimal disk in which large planets had not formed.

Following the discovery of the first Trans-Neptunian Object (TNO) by Jewitt and Luu [8], of order 800 TNOs and Centaurs have been discovered, confirming that there is indeed a 'Kuiper Belt'. The Kuiper Belt is not the cold quiet place which many expected. Instead, we have found a dynamically excited (random speeds much larger than would have allowed the accretion of these objects) and heavily depleted (much less material than would have allowed them to accrete) belt of objects. Numerous questions have sprung from this discovery:

- *What caused the dynamical excitation in the belt?* Current suggestions include: a close stellar passage [9], the passage of either Mars–Earth size bodies [10] or of a nascent Neptune into this region [11], adiabatic capture of TNOs into orbital resonances with Neptune as it migrates outward [12] or displacement of secular resonances in that region. All these scenarios have been developed despite the dynamical structure of the Kuiper Belt being poorly understood. Each of these scenarios provides a unique signature in the orbital dynamics of the region. Only an extensive catalog of orbital information will reveal the truth.
- *Can objects form in the region beyond 50 AU?* Currently there are no objects on circular orbits beyond 50 AU from the Sun. Why? Again a number of explanations have been proposed [9,13]. Perhaps a close stellar encounter would truncate the disk at some radius. Perhaps the Sun was born in a nursery of stars and photo-evaporation removed much of the material. Alternately, recent modelling suggests that the actual process of dust accretion and growth may not function on rapid-enough time scales in this region. A survey covering a wide area of the ecliptic will allow the detection of the apparently-rare objects in this region of the solar system.

- *What is the size distribution of material?* Crucial to understanding the processes of dust accretion and planetesimal growth is a measure of the actual *size distribution* of large planetesimals (50–500 km) in the Belt. Are these objects distributed in a 'cascade' of sizes, caused by the competing effects of accretion and erosion, or is the distribution of sizes indicative of only one of these processes? The Belt is now known to contain multiple components and there is growing evidence that these components possess unique size distributions [14–16].
- *What is the largest member of the belt?* Tombaugh's discovery of Pluto was aided by Pluto's close approach. However, there are now reasons from extrapolation of the observed size distribution to expect that Pluto may not be the most massive member of this region [17]. A comprehensive and complete survey has a chance to determine the largest member of the population and thus further guide our understanding of planetesimal accretion.

Currently astronomers only know the structure of this region of the solar system to the first order: the Kuiper Belt contains material and we have some partial understanding of the different types of orbits (as evidenced that every year has seen the recognition of a new class). Our ignorance of the detailed contents of this region severely constrains the understanding of our solar system. Much progress on this topic will be achieved when we have a large ($\sim$1000) database of unbiased well-determined orbits. This requires that the objects have been discovered in a well-characterized survey, i.e. a survey for which the efficiency of discovery as a function of magnitude and rate of motion is determined, and the effective search area is known and where, in addition, a complete group of objects has been followed to the third opposition. Only 3 or more opposition orbits are accurate enough for long-term ephemerides and for precisely determining the dynamical class to which the object belongs (see examples below).

2. The current status

By early 1999 three main components [18] of the Kuiper Belt had been identified (Fig. 1a): the so-called 'classical' Kuiper belt of low-eccentricity orbits beyond 42 AU, the resonant population of TNOs trapped in mean-motion resonances with Neptune (the 2:3, 3:4, and 2:1), and the 'scattered disk' of objects on unusually large-a orbits with perihelion close to Neptune (thought to have been 'scattered' there by strong gravitational interactions). The objects caught in resonance were commonly thought to have been emplaced by resonance trapping during an outward planetary migration of Neptune. But there was a lack of objects at low eccentricity between 37 and 39 AU, and at low-e outside 44 AU at this time. This was puzzling, because orbital stability calculations (Fig. 2) showed that these portions of the Kuiper Belt are perfectly stable over the lifetime of the Solar System. Did this imply a dynamic process that emptied them? The large ratio of 'plutinos' (as objects in the 2:3 resonance with Neptune are called) to objects in the low-e region from 37–39 AU argued for a model with a very slow migration of Neptune and against the competing concept of disturbing the Kuiper Belt by the presence of other small (and now missing) planets. Additionally, the lack of low-e objects outside 44 AU was seen as suggesting the early truncation of the outer Kuiper Belt via a passing star or photo-evaporation of the young distant dust disk (in which case the objects with higher e and $a > 44$ AU were later scattered outwards).

2.1. The MPC database

All published observations are collected by the IAU Minor Planet Center (MPC) in Boston. This is were most modelers get their information about the dynamical structure of the Kuiper Belt.

As of 11 June 2003, the MPC databases contains 804 objects: 677 classified as Classical Kuiper Belt Objects, Plutinos and resonant objects, 85 in the Scattered Disk, and 42 Centaurs. Among them, 291 (36%) have been observed at 3 oppositions or more, and hence have well defined orbits. 118 (15%) others have been observed at 2 oppositions and *may* have decently-defined orbits. Amongst the 2 opposition objects, 53 (45%) have not been re-observed for more than a year, meaning that their orbit was probably wrong, and they are likely lost. Finally, 395 (49%) objects have been observed at only 1 opposition. 103 of them are new objects discovered over the last ten months, and did not come back to the second opposition yet. The other ones have been lost, in some cases because they were faint, or discovered in very deep surveys [19] and were never intended to be followed to determine their orbits.

Although these numbers may seem large enough for many studies, it turns out that a large fraction of this database is nearly useless when one wants to use it for statistical evaluations or detailed study. The database suffers from 2 different biases.

- Many discoveries have occured in non-characterized surveys. Only over the last 4 years have some discovery surveys been correctly characterized in term of magnitude and apparent motion sensitivity. So, the detection bias is known only for a subset of the database.

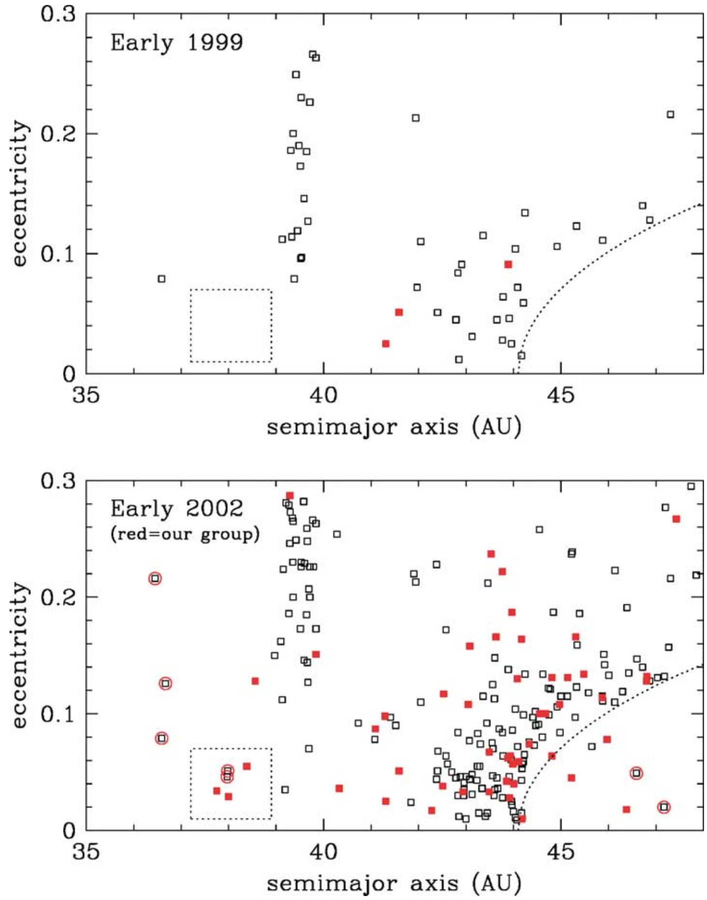

Fig. 1. An illustration of how careful tracking changes the view of the Kuiper Belt. Both panels show semimajor axis a vs. eccentricity e distributions. Upper panel: *all* orbits in the database in early 1999, before we began our CFHT Kuiper Belt work (solid red squares are objects discovered by our group, from Palomar before 1999). Essentially the discovered objects were all assumed to be in the 2:3 resonance (the vertical band at $a = 39.5$ AU) or in the 'classical Kuiper Belt' outside 41 AU; 1 TNO was known in the 3:4 resonance at 36.5 AU. Note the lack of TNOs in the low e regions 37–39 AU and > 44 AU (see text). Lower panel: the *multi-opposition* TNOs in the MPC database in early 2002. Solid red squares indicate objects discovered in our observational campaign (almost all at CFHT), nearly all of which have been tracked to multi-oppositions (see text). In the special regions mentioned above (only), TNOs discovered by others but whose multi-opposition orbits were established due to tracking by our consortium are circled. The view of the orbital distribution of the Kuiper Belt would be very different if the red points were eliminated from the figure.

- Most of the sample of good orbits (i.e. with 3 or more oppositions) are biased by an unknown follow-up bias. When a TNO is discovered, the orbital arc is too short (usually $\leqslant$ weeks) to allow orbit determination: its orbital elements must be 'guessed'. This is not due to poor methods of orbit calculation; one is attempting to compute a $\sim$300-year orbital geometry from a few days or weeks of observation, a problem which is inherently degenerate. The preliminary orbital elements proposed by the MPC are taken to be similar to TNOs already known. Follow-up observations are targeted at the resulting ephemeris and the objects most likely to be tracked are those which are on orbits corresponding to the initial assumptions. Because in many cases little effort was invested in following the discovered objects, only those objects corresponding to these assumptions were recovered in the years after discovery. Hence the known structure of the belt was self reproducing and interesting new orbit types are preferentially lost.

Note that some of the surveys were never intended to produce accurate orbits, but rather to get other types of information. For example, some surveys were intended to determine the Cumultive Luminosity Function [16,19–21], trying to infer the TNO size distribution. Other surveys were searching for the outer edge of the Classical Kuiper Belt [22]. This only require few observations, since the distance to an object can be fairly well determined (10%) with only a one day arc. Almost all objects in these surveys are too faint to be targeted for follow-up observations.

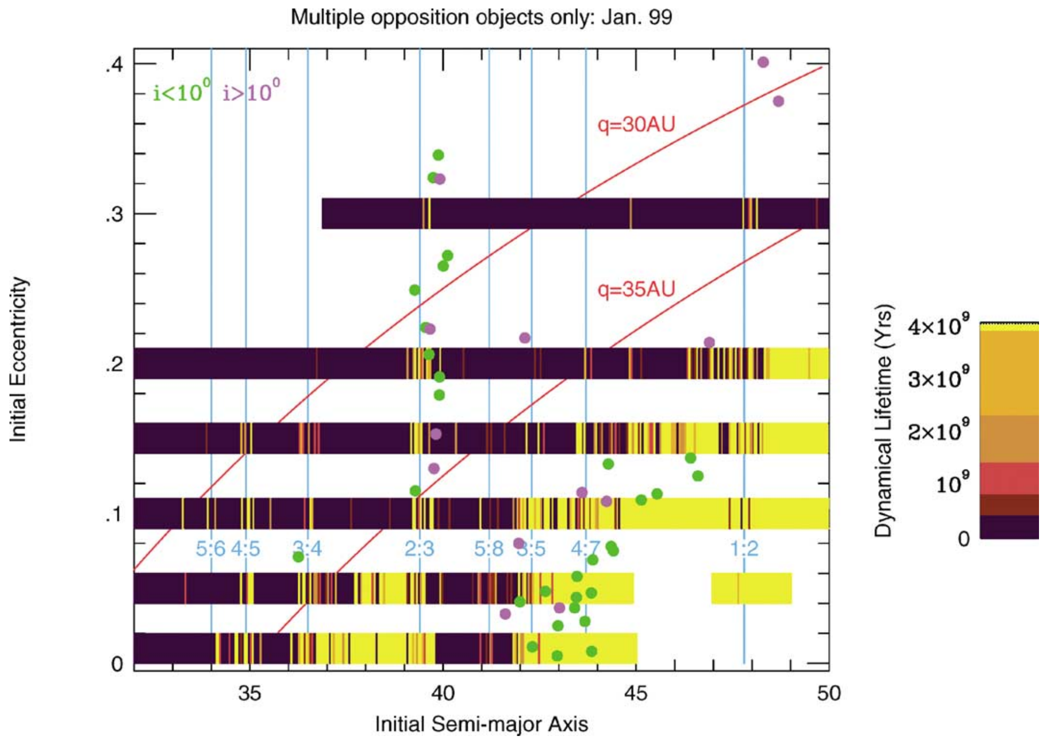

Fig. 2. The a/e distribution of TNOs in early 1999 compared against the colour-coded orbital stability map of Duncan et al. [25]. Objects in yellow regions are dynamically stable over the age of the Solar System and should be populated unless some physical mechanism emptied these regions. Compare with Fig. 1.

These issues make it very difficult to use the current MPC database to obtain a precise image of the Kuiper Belt, due to the role that necessary assumptions have had on the catalogue.

2.2. *Our work*

Starting in summer 1999, our team conducted a series of discovery and recovery observations, trying to avoid all the biases described before. Out of the various observing runs, we discovered more than 120 TNOs and Centaurs. In year 2000 only, we discovered 73 objects, amounting to roughly half the total discoveries of that year. For some of the discovery observations conducted with the 3.6 m CFH telescope, we determined the sensitivity of discovery by implanting artificial moving objects of random magnitudes and rates of motion in the images [23]. Fig. 4a shows the efficiency as a function of magnitude of the object. One can see that only 90% of the surface area of the detectors is effectively used for discovering objects, due to background confusion from stars and galaxies and the presence of gaps in the CCDs in mosaic cameras. The discovery efficiency drops to 50% of its maximum at magnitude $m_R \sim 24$. The rate of motion efficiency curves presented on Fig. 4b differ slightly for bright and faint TNOs. While the discovery efficiency is almost constant for rates larger than 2 arcsec/hour for bright objects, the efficiency drops with rate of motion for the faint ones. This occurs because faint objects trail their signal into indetectibility near the magnitude limit. For all objects, the efficiency decreases when the rate of motion is below 2 arcsec/hour, corresponding to objects further than 70 AU when observations are done at opposition which thus move too slowly for their motion to be detected under the time spacing of the observations.

In one of the characterized discovery runs, we found 38 objects for which we could obtain a second night observations in the same observing run, thus obtaining a ‘provisional designation’ from MPC. We then followed *all* these objects to multi-opposition, and this is the sample used to derive the population fractions in the following.

We have been tracking all the objects that we discovered, and worked very hard to retrieve all objects that are not at their initial predictions to thus eliminate the follow-up bias mentioned earlier. We have additionally invested a great deal of telescope time since 1998 tracking TNOs discovered by other groups, sometimes producing dramatic orbital revisions. This dogged pursuit of objects is the only way to remove the bias induced by placing objects on assumed orbits like those already known. As a result of this effort (see Figs. 1 lower panel, and 3), our consortium is essentially entirely responsible for ‘filling’ the two

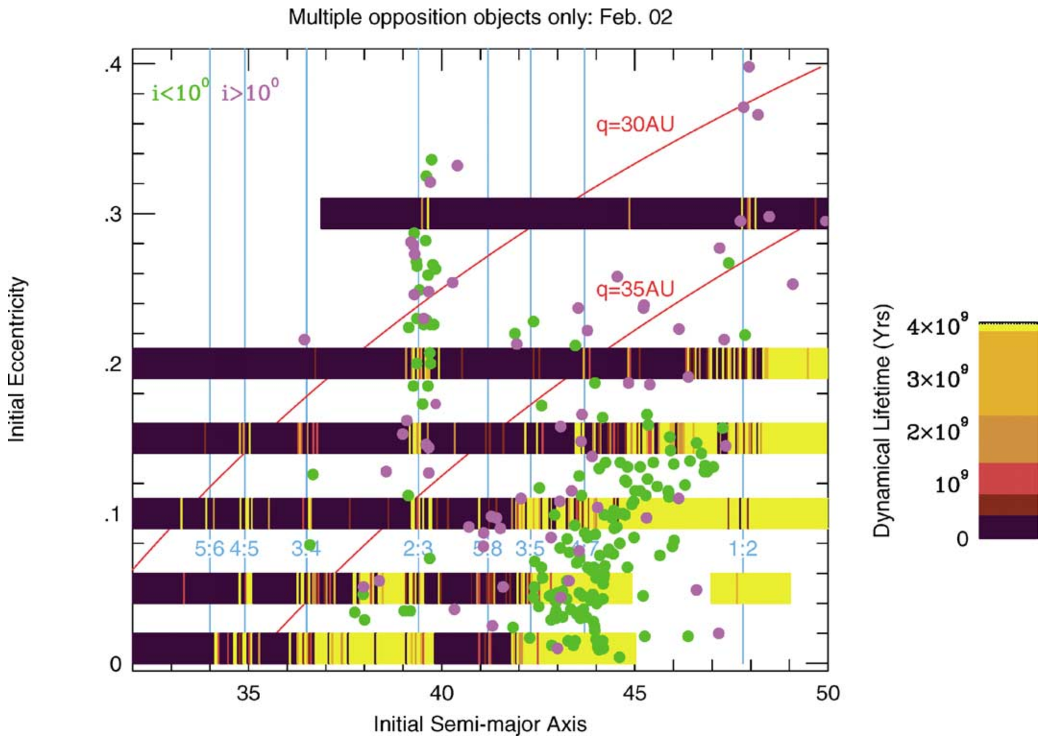

Fig. 3. The a/e distribution of TNOs in early 2002. See text and Fig. 1.

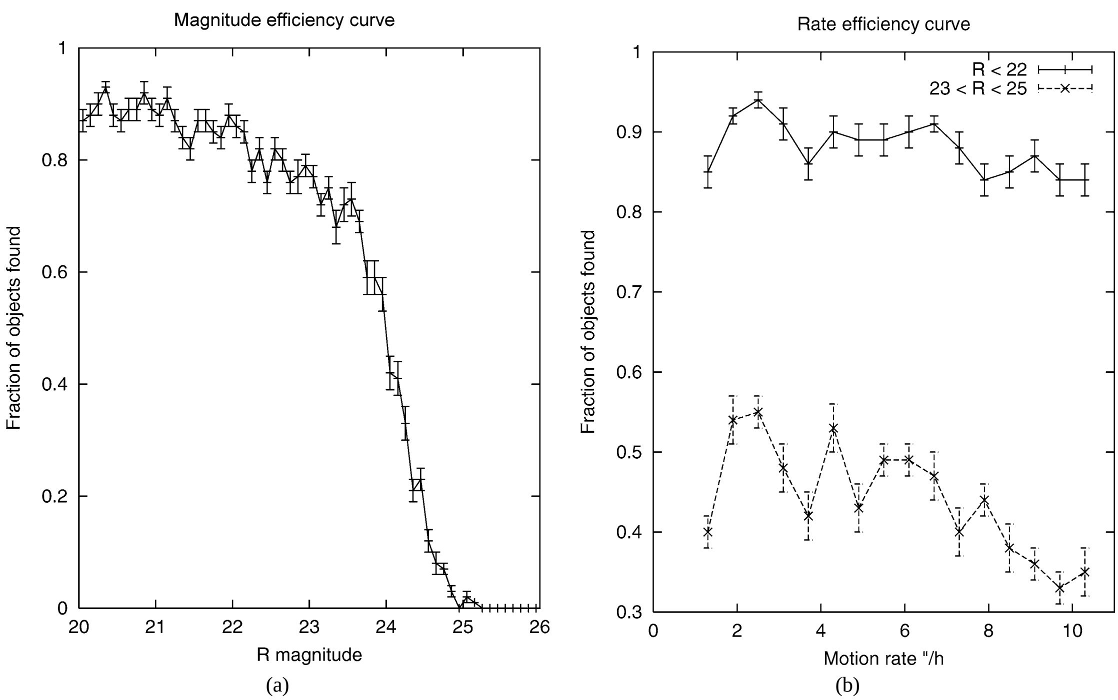

Fig. 4. Sensitivity curves for our 4 night July 1999 discovery run: (a) Sensitivity versus magnitude; (b) Sensitivity versus rate of motion. Solid line: objects brighter than magnitude $m_R = 22$. Dashed line: objects with magnitude m_R in the range 23–25.

previously unpopulated regions of orbital space, clearly exposing the problem of the assumed orbits. The low-e region from 37–39 AU contains objects that are especially bright, and so the lack of multi-opposition orbits coming from all other tracking campaigns is due to the systematic assumption of plutino orbits and subsequent loss of 'nearby' TNOs that are not members of this class. This is also partially responsible for the over-estimation of the 'plutino fraction' of the Kuiper Belt [15]. The low-e region outside 44 AU is difficult to find objects in due to their faintness (the higher e objects with $a > 44$ AU are all found near their perihelia when they are brighter). We now understand the lack of objects in this low-e region as being influenced by the systematic biases in the initial orbit estimation; we feel the chief problem has been insufficiently vigorous pursuit by some teams of their discovered objects, which forces the MPC to make arbitrary choices and introduce biases.

As another example of how our program broke these biases, the population of the so-called 'scattered disk' (on very large and eccentric orbits) has been estimated [15] at 30 000 objects bigger than 100 km diameter based on an 'apparent' fraction of 10% inside the discovery opposition, but the clear identification of such objects requires high time-sampling of the orbit for the first few months and then the following year. Subsequent tracking (much of it by our consortium) showed that other objects in the sample were scattered disk objects, and our tracking of *our* group's sample shows an apparent fraction of 20–25% to be on such high-e orbits, increasing the population of this component of the Kuiper Belt (which stayed undetected due to these tracking biases over the first several years of Kuiper Belt studies).

The case of Plutinos (objects in the 3:2 mean motion resonance with Neptune) is also interesting. In 1998, Jewit et al. [18] reported an observed fraction of Plutinos of 35–40%. Modeling their survey, the authors estimated a real fraction of Plutinos of 10–20%. With more objects discovered, Trujillo et al. [15] revised these numbers to an observed fraction of $\sim$8%, and a modeled fraction of $\sim$4%. Our data seems to imply that the observed fraction is $<$3%. This last number is an observed fraction, as opposed to the modeled fraction mentioned above, which typically gave a value of half the observed fraction. The bias corrections involved in the previous works are very complex, having to deal with the follow-up bias, size distributions, and the unknown orbital distribution of the belt.

We also demonstrated the existence of dynamically very interesting objects, with large perihelion distances, and large semi-major axes. In February 2000, Millis et al. [24] discovered the object 2000 CR_{105}. From the discovery observations, it seemed to be on an unusual orbit, and we decided to follow it. We re-observed it in March of the same year from CFHT and realized that this objects had a very large semi-major axis. We then invested large amounts of telescope time to recover it in November 2000, February, March and December 2001 to determine and secure its orbit. We proved that 2000 CR_{105} has an orbit with $a = 221$ AU, $e = 0.800$, $i = 22.758°$ and perihelion distance $q = 44.14 \pm 0.02$ AU [23]. Similarly, we firmely established that the TNO 1995 TL_8 has a high perihelion of 40.08 ± 0.02 AU, with $a = 52.5 \pm 0.02$ AU. From the very short time during which these objects are visible, we estimate that the number of objects with diameter larger than 100 km in the Extended Scattered Disk may be of order 10^6, 1 to 2 orders of magnitude larger than the previously estimated populations of the Classical Kuiper Belt [23].

Our past survey, as well as all other current or pending surveys aimed at producing acurate orbits are faced with two major problems. Because of the steep slope of the luminosity function [16], most of objects will always be discovered in the half to one magnitude just below the limiting magnitude, and more will be discovered in the best observing conditions, when the limiting magnitude is fainter. It follows that the telescope needed for follow-up should be at least of the same size as the one used for discovery, which puts some strong logistical constraints. Unfortunately, asking for recovery time is not as apealing for Time Allocation Committees as asking for discovery time, which limits the chance to get the proposal approved for individual runs. From this, one clearly sees the urgent need for the CFHTLS Ecliptic Survey presented below, and for an international consortium for TNO follow-up and orbit determination.

3. The CFHTLS ecliptic survey

Scientific progress in the field of Kuiper Belt studies now requires the acquisition of a large ($\sim$1000) and well-characterized TNO data set which is free of orbital bias *and* which furnishes enough 'interesting' objects (rare on the sky) to improve our understanding of portions of the Kuiper Belt. Insight into the mysteries mentioned in the Introduction is limited by the lack of completely-documented and uniform surveys which locate *and track* objects so that relative belt populations can be reliably determined. Correctly determining the orbital structure of the outer Solar System is a critical step for theoretical modelling of the Kuiper belt; similar modelling for the asteroid belt over the last 5 years, using a few well-characterized surveys, has produced excellent advances in understanding the structure of the inner solar system, the distribution of the near-Earth objects, and the impact rates on the terrestrial planets.

The Canada–France–Hawaii Telescope's Legacy Survey includes an ecliptic survey component intending to provide an analogous advance in our understanding of the outer Solar System. While large numbers of new objects are needed in order to obtain a good statistical understanding of the belt, the compilation of this orbital information occurs over a 3–5 year time scale. In the mean time, rare ‘special’ TNOs will be studied in detail, and will help improve our knowledge of the Kuiper Belt. Examples of especially interesting objects are:

- the rare ‘bright’ objects (3–5% of the sample) for which very high quality colors and even spectra can be obtained;
- the rare ‘distant’ objects (those outside 48 AU, about 5–10%) which probe the puzzling ‘outer Kuiper Belt’;
- binaries, which tell us about the mass-evolution history of the belt;
- things we cannot yet imagine! (e.g., even 10 months ago binaries were *not* expected to be found in the numbers that they have been).

3.1. Long-term tracking requirements

Reliable tracking of TNOs requires the following minimum strategy, which induces a natural 3-year time scale into the problem.

1. *Discovery* is done within 15 degrees of opposition to maximize the apparent motion and thus sensitivity to distant objects (at 50 AU motions are roughly $2.6''$/hr). Observations on 2 nights in the same dark run generate reasonable estimates of orbital inclination and nodal longitude, as well as an heliocentric *distance* (not semimajor axis) reliable to 5–10%.

2. *Check-up* observations 2–3 months after opposition are necessary in order to extend the baseline of a few days by an order of magnitude. This reduces the distance error and the uncertainty for the recovery the next year. Owing to the temporal proximity to the discovery, 1 night (3 images) of check-up observation per object is sufficient at this stage. At this stage, the object is relatively secured till the next opposition.

3. *First Recovery* observations in the year after discovery. These represent the most difficult observations due to the fact that the semimajor axis and eccentricity can not be well determined in the first year. For example, our Jan 2000 CFH12K (field of view $42' \times 28'$) recovery of the TNO 1999 CZ118, observed over a 3-month arc in 1999, was $23'$ from its predicted location, our recovery observations resulted in a large revision to the assumed orbit. Even though the heliocentric distance was indeed correct to 5%, the positional error accumulated over 1 year had become $\sim 20'$. This is an extreme case, but experience shows that ∼10% of the (thus most interesting) TNOs will be lost if a mosaic camera is not available for some 1st recovery observations two months later. Small field-of-view imagers on other telescopes will be used to attempt first-recoveries, and the few missing objects will be pursued with mosaic cameras (with MEGACAM potentially needed in extreme cases). In order to prevent confusion with near-Earth or main-belt asteroids, and to be sure that the recovered object is indeed the original object, astrometric measurements on 2 (preferably nearby) nights are necessary at this stage.

4. *Second Recovery* observations occur 2 years after the initial discovery, and serve to refine the orbit determination. Several past examples show that semimajor axes can still change considerably at this stage, even though the ephemerides are much more firm.

As an example of this process, consider the TNO 2000 FB8 with $m_R \simeq 23.8$, discovered in March 2000 at CFHT (seen on 2 nearby nights). This object was tracked from the VLT UT1 in July 2000 for its check-up observation, and then had its first recovery from the same telescope in February 2001. The second recovery occurred from the Magellan telescope in February 2002. As a second example, the TNO 1999 OY3 as discovered using only a single night in July 1999 at CFHT, but was re-observed (thanks to the real-time detection at CFHT) on two different nights a few weeks later, once at the CTIO 4 m and once at the Palomar 5 m. The first recovery observation was in fact performed at CFHT and the second recovery at Calar Alto. Frequent and well-coordinated observations are necessary to prevent object loss and/or duplicate observations.

In our experience, the problems introduced by recovery nights lost to weather or objects falling in front of stars and on chip gaps necessitate that, with the above strategy, $\sim 5\times$ the discovery time must be available, if all objects are to be tracked. We feel that an unbiased approach to recovery is an essential step to understanding the orbital structure of this region of the solar system.

3.2. The ecliptic survey setup

The ultimate goal of an ecliptic-plane survey should be to cover 20 000 square degrees, the entire sky within 30 degrees of the ecliptic. This is clearly impractical on a 5-year time scale for Megacam. This is also no feasible from CFHT since declinations less than −25 degrees are undesirable: the point 30 degrees south of the ecliptic in June is at −53 degrees declination.

Moreover, one must avoid placing too large a burden on recovery facilities tracking newly-discovered objects so as not to risk impairing the scientific interest of the survey as a whole. Therefore, it is better to keep the rate of discoveries constant at a rather low level and the faintness of the targets above some reasonable magnitude threshold. Experience have shown that objects as faint as $r' = 24$ or fainter are too faint to be tracked economically and are not useful for physical study. Finally, the survey must contain the bulk part of the recovery, so that other tracking facilities will be used only for those objects falling out of the surveyed portion of the sky at recovery time, or on chip gaps or in front of a star.

3.2.1. Target fields and observing constraints

The current design of the survey should detect one object per Megacam field when near the ecliptic. The density of Kuiper Belt objects is a strong function of ecliptic latitude. Even a few degrees North and South of the orbital plane, the density of objects begins to drop. The survey observations should be made on or near ($\pm 2^\circ$) the ecliptic plane to produce the maximal discovery rate. The short exposure times ensure that detected objects are bright enough to track easily and short exposures are of course necessary to permit wide sky coverage.

A major goal of the survey is to discover the spatially rare objects as these are most likely to lead to major advances in this field. Given that the discovered objects will be imaged many times at other facilities, photometric precision and image quality are not driving factors in these observations. Rather, correct time spacing of observations and coverage of the ecliptic are the major concerns. Careful attention must be paid to the constraints imposed by the timing needs of when exposures within a night and days/weeks later need to be obtained. Given estimated throughputs of the camera it is expect that the survey will operate sufficiency well even with image quality as poor as $1.1''$.

3.2.2. Filters

The filter choice remains open to optimization with the secondary science goals of the Ecliptic survey. For the Kuiper Belt science, keeping any given 'triple' in a single filter is crucial for the data pipeline because objects near the noise limit fade in and out of various filters and strongly increase the false detection rate. However, the 4 triples *could* each be in a different bandpass, and the two nailing observations in yet another. Various secondary science goals will have different filter optimizations.

Kuiper Belt objects are mostly red to flat in their spectral colour. Our previous surveys have all operated in the R band where sky levels and object brightnesses provide the best contrast. Given the estimated throughputs of Megacam, the survey will be most efficient if the discovery observations are made in the r' or g' bandpasses. Once the real performance have been measured, the actual exposure time for all filters will be adjusted to account for the typical spectral colour of the Kuiper Belt objects.

3.2.3. The discovery-tracking sequence

The base unit is a 'block' of 'triples'. A triple consists of three 2.35-minute images of a field in one filter, requiring 11 minutes of telescope time when overheads are included, allowing a 16-square degree 'patch' of fields to be imaged in a 3-hour 'block'. For non-moving object work (study of our galaxy, stellar populations, and white and brown dwarfs), summing the three 2.35-min exposures should yield a depth of about $m_R \simeq 24.4$ (5-sigma) in $1''$ seeing.

The following compromise strategy as been designed:

- *Discovery*: Triple on a 16-sq. degree sky patch (3 hr of telescope time) at opposition in a single filter (r').
- *Nailing*: One image of the same patch within 24–72 hours in r' filter (1 hour).
- *Check-up*: Another triple on the original patch in a single filter (g') in the first 8 days of the dark run 2 months later (3 hr).
- *Repeat*: Three years after the discovery opposition the patch is imaged again as a triple in a single filter (r'). Typical TNO motion will be 1 degree per year, and assuming contiguous patches on the sky the majority will be recovered. Although the outer solar system science would most benefit from a 'repeat' 2 years after discovery, galactic proper motion studies prefer 3–5 years.
- *Repeat Nail*: One image of the same patch within 24–72 hours in r' filter.
- *Repeat Check-up*: Another triple on the original patch in a single filter (i') in the first 8 days of the dark run 2 months later.

In the above strategy all exposures are 2–2.5 minutes long, and each field is imaged 7 times in the first year and then 7 times 3 years later. For each year, 404 square degree of sky will be imaged, corresponding to 2828 exposures per year, or 18.1 nights per year.

We are currently investigating the efficiency of linking 2 month arc observations 3 years apart. This is the current status of the design, but may lead to too much confusion between discovery (and check-up) observations, and the recovery 3 years later. Another possibility which keeps the same load for the Ecliptic Survey, the same area coverage, and does not affect the secondary science goals is to move the *Repeat Check-up* observations to second opposition recovery. In this case the discovery patch would be re-imaged 10-month after discovery, and the fourth year epoch will be limited to the repeat triple and the nailing observation. The load will then be as detailed in Table 1, using about 23 nights per year for the first 3 years, and then some smaller fraction for the remaining 3 years, with a minimum in year 5.

3.2.4. Time constraints and requirements

Moving-object detection codes are most effective when the objects move by 1.5 times the seeing between exposures. Kuiper belt objects at 100 AU will have a retrograde sky motion rate of $\sim 1.4''$/hr when viewed at opposition. The observing sequence should be designed to allow detection in seeing as poor as $1.1''$ FWHM. These constraints result in an inter-image spacing of approximately 1 hr.

Table 1
Telescope time load of the CFHTLS Ecliptic survey in the alternative scenario (see text). For lines 2 to 4, the table give the number of images per field for discovery year (discovery, nailing, check-up; line 2), for second opposition recovery (line 3) and finally recovery (line 4). Line 5 gives the area covered by discovery observations, line 6 the number of exposure taken per year, and line 7 the number of nights per year required

Year	1	2	3	4	5	6
Discovery	7	7	7			
Second opposition		3	3	3		
Fourth opposition				4	4	4
Square degree/year	510	300	400			
Exposure/year	3570	3630	3700	3240	1200	1600
Night/year	22.9	23.3	23.7	20.8	7.7	10.3

Because of the need to have 1 hour between each of the images (the 3rd image being taken 2 hours after the first), the timing constraints are critical; once an observation block is begun it should not be stopped. With fewer than 3 images the data from the first portion of the triplet becomes useless for automated moving-object detection.

This program inherently introduces strong timing constraints on the CHFT queue. There is some flexibility assuming that the Ecliptic survey coordinator can interact with the queue on a short time scale; for example, should a discovery triplet block be unable to acquire its second or third image due to weather, the first image could be used as the nailing image if the patch can be imaged with a new triple during the following nights. The queue could also contain ‘Check-up’ triplets to be taken at the last half of nights positioned two months *before* opposition, thus giving the queue maximum flexibility. It is important that all Ecliptic data be obtained in identical sequences regardless of its position relative to the ecliptic; high ecliptic latitude data is not expected (at this time) to yield very many TNOs, but any systematic data thus obtained will provide useful constraints to Solar System science.

Due to confusion with background stars/galaxies and the presence of chip gaps, roughly 10–20% of the objects will require additional imaging, which will mostly be done at other telescopes.

4. Expected output

To first-order the luminosity function of TNOs can be described by a single power-law,

$$\Sigma(m_R < R) = 10^{\alpha(R-R_0)} \tag{1}$$

where $R_0 = 23.5 \pm 0.2$ and $\alpha = 0.69 \pm 0.3$ [16]. This function provides the distribution of material on or near the ecliptic. The limiting magnitude for a single exposure in r' filter will be approximately 23.2–23.5. Given this distribution and the limiting magnitude, an object will be discovered in almost every Megacam field. At the end of the 6-year CFHTLS Ecliptic survey the $\sim$1000 new detections will have been discovered and had their orbits determined.

As a first result, we will obtain a precise luminosity function for objects brighter than magnitude 23.5 from a large homogeneous data set. Coupled with a detailled physical study of the brightest objects, this will lead to the first reliable size distribution determination, down to about 100 km. The slope of the size distribution is a good indicator of the process that shaped the belt, either accretion, collisional erosion, or a mix of both. This will also tell us the maximum size of accreted bodies as a function of distance, and thus give strong constraints on accretion models.

With an unbiased orbital database of $\sim$1000 objects, we will have a reliable estimate of the relative importance of the dynamical subpopulations in the Kuiper belt and the scattered disk. Each proposed formation and evolution scenario for the Kuiper belt having a very distinct dynamical signature, we will be able to select the correct one.

Kuiper Belt object colours that come from the survey data directly will be of low quality (a few tenths of a magnitude uncertainty) because the steep luminosity function implies most detected objects will be near the limit; high S/N colours needed for physical studies will come from work on other telescopes.

Among the detected objects, more than 100 will be bright enough for high-quality photometric study and colour index determination, and about 50 will be reachable for spectrographic study. About 10–20 binary KBOs should be discovered. And lastly, the things which are the most interesting are likely that which we cannot as yet imagine.

Acknowledgements

The preparation of this Compte-Rendu has been made possible by the efforts of a large international team, including: A. Campo Bagatin, A. Doressoundiram, T. Grav, M. Holman, J.J. Kavelaars, A. Morbidelli, O. Mousis, J. Parker, P. Rousselot, H. Scholl, C. Veillet.

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