The Southern Edgeworth-Kuiper Belt Survey

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The following errata were made by the author in response to an examiner's report. Each alteration is denoted by the page number and within the context of the relevant paragraph.
On page 5:

The EKB provides a stringent test of both planetary formation models since for any model to be valid it must account for the mass and size of the TNO population. Theoretical models suggest that the amount of dust in the early solar system is comparable to the measured mass of dust around \( \beta \) Pictoris (Jane Luu, private communication) while thermal emissions around dusty young stars including \( \beta \) Pictoris, HR 4796 and \( \epsilon \) Eridani and others provide circumstantial evidence for the presence of an extra-solar planetary system and a debris disk, which begins at similar scales to the EKB, around each star (Smith and Terrile, 1984; Backman and Paresce, 1993; Artymowicz, 1997; Koerner et al., 1998; Spangler et al., 2001). Hence, understanding the role of TNOs in the formation and evolution of the solar system may also provide a link to the formation of planets around dusty young stars.

On page 7:

While some disks are due to debris from planetary or planetesimal body collisions, other stars appear to have disks which are the progenitors of planetary systems (Fischer and Pfau, 1997; Ozernoy et al., 2000; Greaves et al., 2004).

On page 12:

As well as the lack of classical TNOs beyond 50 AU, the second surprise has been the recent discovery of several non-resonant TNOs with inclinations up to 30\(^\circ\), as shown in the centre plot in Figure 1.7, (Jewitt and Luu, 1995; Jewitt et al., 1996; Jewitt et al., 1998; Trujillo et al., 2001; Trujillo et al., 2001). While interactions with Neptune explain the higher inclinations of resonant TNOs, there is no equivalent mechanism for this group of objects which are nominally included here as members of the classical EKB. These objects have spurred the debate that the classical EKB is made up of 2 distinct populations, one of which is dynamically cold and resides in the invariant plane (Hahn and Malhotra, 1999; Allen et al., 2002) while the other is dynamically warm.

On page 13:

However this theory is yet to be substantiated, as it suffers from small number statistics' because of the limited sky coverage to date and because most surveys have been conducted in the Ecliptic where inclined objects spend preferentially less of their orbit.

On page 14:

TNOs within the resonance EKB also have semi-major axes between 37 (within the 4:5 resonance) and 48 AU (within the 2:1 resonance).

During the final stages of planet formation the giant planets began gravitationally clearing the remnant planetesimal debris from which the planets had been formed. Due to conservation of energy and momentum this scattering caused each planet's orbit to evolve (Fernandez and Ip, 1984). According to this theory Jupiter and Saturn were large enough to scatter the planetesimals out of the solar system and into the Oort cloud which would cause their orbits to shrink inwards. In the case of Uranus and Neptune their smaller mass caused them to gravita-
tionally scatter their remnant planetesimals towards the Sun, causing Neptune's orbit in particular to expand significantly and allowing its orbital resonances to sweep through a large portion of the outer solar system.

However, initial models have suggested that resonant TNOs should be concentrated at the 3:2 and 2:1 resonances, while the other resonances should be less heavily populated (Malhotra, 1995), but this prediction is strongly dependent on the original distribution of the TNO population. As shown in Figure 1.8, currently the 2:1 resonance is a factor of 4 less populated than the 3:2 resonance.

As shown in Figure 1.10, scattered TNOs typically have semi-major axes of more than 250 AU. Such extreme orbits place these TNOs at great distances from the Earth for hundreds of years making detection difficult (Trujillo et al., 2000).

There also remains an open question as to whether the mass of the EKB is tied up in the largest or smallest objects, a question which requires that both the small and large ends of the size distribution be measured (Chiang and Brown, 1999; Bernstein et al., 2004).

There are two main strategies one can use in order to look for a population of outer solar system objects. The 'pencil-beam' strategy is to observe a small area with a long exposure to maximise the depth of field. This strategy takes advantage of the increased sky density of TNOs at fainter magnitudes. As a result, surveys of this type are able to detect less distant smaller TNOs as well as larger TNOs further out in the solar system.

In the past two main techniques have been utilized in the search for slow moving objects. The first technique was to search for TNOs by observing a small area of sky down to the faintest limiting magnitude. These 'pencil beam' surveys were designed to maximize the typically limited amount of observing time and the probability of detecting a TNO. The second technique was to survey a large area of sky albeit at the expense of a relatively bright limiting magnitude. The advantage of a pencil beam survey is that large numbers of TNOs can be observed, while the advantage of a wide area survey is that rare, bright TNOs will be detected.

As a result of the drawbacks of the initial observing strategy, a modified observing strategy was implemented in November, 2001. This new strategy allowed fields to be observed a maximum of 40° from opposition but gave fields within a degree of opposition the highest priority. The other major change was to allow all three observations to be taken a minimum of three hours apart.
As the bulk of TNOs have orbits with eccentricity < 0.4, a typical strategy for follow-up would be to observe the cyan shaded region and then, if the TNO failed to be recovered, the grey region would then need to be observed.

On page 42:
To add the synthetic objects, the canonical PSF is scaled to the appropriate height using the zero point measured in Section 3.5 and inserted in the chip image at the desired location. As the exposure time of each image is short we assume that the trailing of distant solar system bodies will be unnoticeable. Accordingly the synthetic objects are added as point sources with no trailing.

On page 49:
In this way all 4 samples were made to be as realistic as possible and were treated in the same way by the search algorithm as the transient detections. As a result, these 4 different samples test the efficiency of the selection criteria to detect TNOs while rejecting asteroids, given perfect noiseless magnitudes and positions for each detection, and thus represents the best possible TNO detection efficiency achievable for our Survey.

On page 51:
This sample contained 52 known TNOs, more than 60% of which have been observed at 2 or more oppositions. It should also be noted that the majority of these objects will be well below the detection threshold of the survey, with only 3 of the 52 minor bodies having a magnitude brighter than 21 at the time they were located in the survey fields.

On page 61:
Also shown in the bottom right-hand plot of Figure 3.9, the further from opposition an asteroid is observed, the smaller it’s apparent angular velocity. As a result, this criteria is able to exclude ≈10% of the asteroids observed at more than 50° from opposition.

On page 67:
A TNO typically has a small inclination which results in a zero angle to the ecliptic while asteroids, with typically much larger inclinations, can exhibit a wide range of angles making this criteria a potentially strong discriminator between TNOs and asteroids.

To use this TNO-like characteristic as a criteria for excluding less distant solar system bodies, the first step is to calculate the Earth’s vector of motion, since it lies in the ecliptic,...

On page 72:
As demonstrated in the plots shown in Figure 3.14, the most distinguishing feature of the two known TNOs to fail the criteria is their significantly high eccentricity. Both objects, marked in red, have orbits with eccentricity close to unity which invalidates the assumption of zero intrinsic motion for TNOs. For the failed TNO with a semi-major axis of 98.5 AU this resulted in a higher than expected apparent velocity while the other failed TNO was sufficiently distant
that its apparent motion passed this criteria, but its high inclination resulted in it lying just above the acceptable angle to the Ecliptic.

On page 85:
After careful scrutiny of all follow-up observations, no TNO-like moving object was recovered. However as our detection is unlikely to be 100% even for relatively bright objects, this non-detection does not immediately rule out this object as a possible low-inclination TNO. The object might have moved between fields during the observations and so wasn’t detected in the 3 frames. It might also be that the object was observed 3 times but on different fields and so a wider search across all of the observed fields might yield the object.

There is also the possibility that this candidate is a high eccentricity TNO which cannot be ruled out until follow-up observations of the grey survey region are conducted.

On page 103:
Of these 6 TNO candidates, 3 are serendipitous recoveries of previously detected TNOs. Previous tests showed that 3 of the 52 known TNOs to be located in our survey fields had magnitudes brighter than 21. Our serendipitous recoveries of 2002 JR146 and 1999 DE9 match 2 of these objects while 1996 GQ21 was expected to be at a magnitude of \( \approx 21.5 \), given an albedo of 0.04. Thus we recovered three out of the only four known TNOs in the data bright enough to be detected, a strong indication that the data reduction pipeline and orbit fitting software are powerful tools for finding TNOs.

On page 109:
As given in Schulz (2002) and reproduced here, the commonly accepted range of values for the parameters \( \alpha \) and \( m_0 \) are given in Table 5.3 and show that there is still significant contention between the various groups. Furthermore, it has been suggested that the CLF behaves differently at different magnitudes such as recent work by Bernstein et al (2004) which shows that beyond 25th magnitude a single power law is a very poor fit to the data. The same could also be true at the bright end of the CLF.

On page 112:
The best fit to our data was determined from a least-squares fit to our six points which gave \( \alpha = 0.756 \) and \( m_0 = 21.96 \).

On page 114:
Recently dynamical simulations of the evolution of the outer solar system have shown the EKB as a feasible source of Centaurs, providing the first step for a theoretical foundation to the link between TNOs, Centaurs and short-period comets (Duncan et al., 1987; Duncan et al., 1988; Holman and Wisdom, 1993; Levison and Duncan, 1993; Levison and Duncan, 1997; Duncan and Levison, 1997; Morbidelli and Valsecchi, 1997).

On page 119:
...our candidates cover a broad range of colours from neutral to red but the sample is too small and the errors too large to probe the issue of a continuous versus bimodal colour distribution, in fact the data are consistent with the hypothesis that all TNOs have the same colour, V-R \approx 0.5.

On page 122:

Confirmation that the potential discoveries have been correctly classified will only come from recovery observations, which have currently only been carried out for one of the TNO discoveries. These follow-up observations failed to detect any objects with TNO-like orbits but as there are several reasons why the candidate could have failed to be recovered, this object has not yet been ruled out as a low eccentricity TNO. Further observations and a wider sky-coverage are required to confirm this object is a TNO, but if it were recovered it would be the largest known body in the classical EKB discovered to date.

On page 123:

The bi-colour nature of our survey potentially made any detections a good sample with which to contribute to the continuing debate over the colour distribution of both TNOs and Centaurs. A comparison with our measured colours to previous measurements of the colour of 1996 \textit{GQ$_{21}$} and 1999 \textit{DE$_{9}$} (Delsanti et al., 2001; Boehnhardt et al., 2002) were in good agreement. The colours of the TNOs ranged uniformly from neutral, V-R \sim 0.4, to very red, V-R \sim 0.7 showing no signs of the bimodality seen by Tegler and his colleagues (Tegler and Romanishin, 1998; Tegler and Romanishin, 2000; Tegler et al., 2003) but rather a uniform distribution as seen in several other surveys (Luu and Jewitt, 1996; Jewitt et al., 1998; Barucci et al., 1999; Barucci et al., 2000; Doressoundiram et al., 2002; Hainaut and Delsanti, 2002). However, due to the small number of detections and the large error bars our data could not be used to discriminate between the competing theories of continuous versus bimodal colour distributions. In fact the data is continuous with the hypothesis that all TNOs are at the same colour, V-R \approx 0.5.

Our detections do lend some support to the theory that Centaurs have very similar colours to TNOs, which is expected if they are different evolutionary stages of the same primordial population of minor planets.

References


Barucci, M. A. et al.: 2000, \textit{aj} 120, 496


Duncan, M., Quinn, T., and Tremaine, S.: 1988, *apjl* 328, L69
Disclaimer

I hereby declare that the work in this thesis is that of the candidate alone, except where indicated in the text, and as described below.

The data presented in this thesis was produced by the SEK Survey whose members comprise the candidate, Charles Alcock (PI), Brian Schmidt, Jeffrey Goldader, Tim Axelrod, Kem Cook and Stuart Marshall.

Approximately half of the human check of objects was completed by Lachlan Campbell, Lorenzo Faccioli, Jeff Goldader, Laura Marian, Albert Price and Mitch Struble. The remaining half of objects were checked by the candidate.

Follow-up observations of the Survey's first potential TNO were taken and analyzed by Stefan Keller in 2004.

The reduction and analysis of all SEK data was undertaken by the candidate.

Rachel Moody
October 2004
Acknowledgments

Over the course of my thesis I have moved house 9 times, lived in 3 different countries, survived a bushfire (although my telescope and data did not!), given up a dog and two cats and acquired 28 fish and a husband. Thinking about all of this I realise that there are many people to whom I am indebted and I would like this opportunity to say thank you.

To my collaborators my deepest gratitude for giving me the opportunity to work on such an exciting project. Even now after more than 6 years I still wake up in the morning keen to go to work (well most mornings anyway!). Thank-you Stuart and Kem for getting me involved in almost every aspect of the Survey from observing and telescope maintenance to data management and analysis.

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To Jeff thank you for sharing your office, your time and your shoulder whenever I needed it. Our many talks helped me to keep my mind focused not only on my thesis but what I want to do with life after the thesis.

To Brian you have been with me through the highs and the lows, through the storms, fire and tears - thank you for taking the journey with me.

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Abstract

This thesis presents the data reduction techniques and results of the analysis of the Southern Edgeworth-Kuiper belt (SEK) survey, an optical survey which covered more than 2000 deg² in searching for rare, bright minor planets in the outer solar system known as Trans-Neptunian Objects (TNOs). During the 3 years in which the survey ran, a total of 4368 fields were observed three times with a baseline of typically 2 days, using the dual camera system mounted on the Great Melbourne Telescope at Mount Stromlo Observatory.

The primary goal of the survey was to have large sky coverage, uniform and well-defined detection limits in magnitude and proper motion, and 2 colour photometry in order to produce a sample of bright minor planets which could be used for further optical and spectroscopic study, as well as provide constraints on current models of the formation and evolution of the solar system.

The uniform and well-defined detection limits in magnitude and proper motion required by the Survey were achieved through the creation of a synthetic population of outer solar system bodies. This population was designed to encapsulate the known properties of Centaurs and TNOs while also sampling a much larger range of objects which may have so far gone undetected. This synthetic population was added to the data at the beginning of the data reduction process in order to appear as real as possible. The identity of these objects was not known until after all the data had been reduced to ensure that the recovery of these objects would closely match the recovery of real objects.

TNOs were extracted from the data using a TNO search algorithm developed to take advantage of the unique features of the survey such as the short baseline and bi-colour observations. This search algorithm was designed not only to accurately select TNOs but also to exclude less distant solar system objects such as asteroids. The search algorithm is defined by 7 selection criteria based on the magnitude, the maximum and minimum apparent angular velocity and the linear motion of the object. The algorithm was found to successfully extract 87% of TNOs and exclude all but 0.01% of asteroids. For fields observed within 30° of opposition, 95% of all TNOs were successfully extracted while 100% of asteroids were also successfully excluded.

A secondary goal of the Survey was to determine orbits for each TNO discovered which would be accurate for the next decade. This was to be achieved by taking follow-up observations of each candidate. To determine the smallest region to search with the highest probability of recovery, software was developed to constrain the range of orbits fitting the short arc of each candidate. These fits can then be propagated to any point in time to predict likely positions for the candidate and in so doing define the search region with the highest probability
of recovery. Tests conducted on this software showed that the predicted recovery region encompassed the candidate’s position in 92% of cases even though the predictions were made for follow-up observations scheduled several years after discovery.

Analysis of the 1993 fields yielded 13 TNO candidates. Upon further inspection of these objects, their range of fitted orbits, and a comparison to known minor planet populations, it was found that 3 of the objects were serendipitous recoveries of known TNOs, 1996 GQ$_{21}$, 1999 DE$_9$ and 2002 JR$_{145}$, three candidates which are potentially new TNOs, two candidates which are potentially new Centaurs and five objects which were not fit by either Centaur or TNO-like orbits and are potentially new asteroids. The potential TNO and Centaur candidates need to be confirmed by follow-up observations.

The detection efficiency and limiting magnitude of the Survey were calculated from the recovery of objects from the synthetic population. While further analysis showed that we may have underestimated our detection efficiency by $\lesssim 4\%$, we achieved a limiting magnitude of $m_R = 19.5$ which is comparable to other large sky surveys using automated data reduction software (Luu and Jewitt, 1988; Sheppard et al., 2000; Larsen et al., 2001).

Based on the assumption that the 3 potential TNOs and 2 potential Centaurs have been correctly classified, the 8 outer solar bodies found by the Survey were used to investigate some of the remaining open questions about the nature of the EKB. The first step was to construct the Cumulative Luminosity Function (CLF) for TNOs. The calculated points from the 6 TNOs lie within the errors given in the literature but are higher than the current best fit to the CLF, which could suggest that for $m_R > 20$ the CLF has a shallower slope than that observed for faint objects.

The Centaur CLF was determined from the 2 potential Centaurs and these values were also found to lie above the CLF calculated in the literature but still within the errors.

The bi-colour nature of the observations made the 8 candidates a good sample with which to contribute to the continuing debate over the colour distribution of both TNOs and Centaurs. V-R colours for all candidates were constructed. A comparison with our measured colours to previous measurements of the colour of 1996 GQ$_{21}$ and 1999 DE$_9$ (Delsanti et al., 2001; Boehnhardt et al., 2002) were in good agreement. The colours of the TNOs ranged uniformly from neutral, V-R $\sim 0.4$, to very red, V-R $\sim 0.7$ showing no signs of the bimodality seen by Tegler and his colleagues (Tegler and Romanishin, 1998; Tegler and Romanishin, 2000; Tegler et al., 2003). Our data also supports the theory that Centaurs have very similar colours to TNOs which is expected if they are different evolutionary stages of the same primordial population of minor planets.
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Chapter 1

Introduction

“In all things of nature there is something of the marvelous”
Aristotle

The last decade has seen a reawakening of solar system astronomy due to the first detection of extra-solar planets and the discovery of a vast population of small, icy bodies orbiting in the outer regions of our own Solar System. These small bodies are known as Trans-Neptunian Objects (TNOs), because they orbit the Sun in a belt beyond Neptune which has itself come to be known as the Edgeworth-Kuiper belt (EKB).

TNOs are made up of some of the least thermally processed material from the primordial debris disk, and thus the orbital distribution, size distribution and chemical properties of these objects could hold key information to understanding the formation and evolution of the solar system. The EKB could also provide a link between our own solar system and the dusty rings observed around young stars which have long thought to have been the birthplace of planets.

However, the outer solar system is a difficult region to study, most of the TNOs discovered have been very small and faint ($m_R > 22$) making them challenging to detect with current ground based telescopes and poor subjects for spectroscopy. Other members of the TNO population spend only a small fraction of their orbits close enough to the Sun to be observed, while larger objects are rare so that considerable sky coverage is needed in order to discover them. All TNOs have orbital periods of hundreds of years so that many observations of an object are required before an accurate orbit can be determined.

The Southern Edgeworth-Kuiper belt Survey (SEKS) is one of the most ambitious searches for bright TNOs in the outer solar system and is the basis of this thesis.

1.1 The Formation of the Solar System

Even though the planets are our closest neighbours in the cosmos, we still do not have a coherent picture of their formation and evolution. This lack of understanding became even more apparent with the discovery of extra-solar planets. Previous theories about the formation of the Solar System attempted to produce
the only known planetary system, our own. However, in 1992 a pulsar was discovered to have two planets in orbit around it (Wolszczan and Frail, 1992). While these planets were the first to be observed beyond our own solar system they were considered an anomaly since they had not been formed from a debris disk like our own planets. However soon after, planets were discovered around stars much like our Sun and so it was expected that these planetary systems would closely resemble our own.

Currently more than 100 extra-solar planets\(^1\) have been detected and as shown in Figure 1.1, none of these planetary systems resemble our own solar system. In most cases the planetary system consists of a massive Jupiter-like planet less than 1 AU from it’s star. While the lack of detected solar systems similar to our own is the result of selection effects, the distinctly different nature of the currently observed extra-solar planetary systems cannot be explained by current models of planet formation. It is hoped that if we can accurately model the physical processes which were important in forming our own solar system, we can begin to understand its relationship to other planetary systems. However, our view of the Solar System is limited to what it currently contains and what processes we see active today.

Models for the formation of our solar system were first put forward almost 300 years ago by Descartes, Kant and Laplace among others. While these first models, which held that the Sun and the planets contracted out of a cloud of dust and gas, still form the basis of our understanding, there is no model which can produce both terrestrial and gas giant planets over the age of the solar system. At present many theories exist as to how planets form but the two currently most supported theories are core accretion and dynamical instability models.

In the core accretion model, the protostellar cloud of dust and gas quickly settled into a disk around the Sun. The dust particles then underwent constructive collisions forming successively larger grains, from millimeter sizes to kilometer sized planetesimals to lunar-sized planetary embryos, until all the available planetesimals in the primordial disk were either accreted into larger objects or dynamically removed. These processes took place in the 10\(^6\) years after the formation of the Sun. At this stage of the scenario there are \(\sim 10\) planet cores of size 1-10 \(M_\oplus\) orbiting on roughly circular orbits. Cores which successfully reach a critical mass in the range 10 – 15\(M_\oplus\) then grow through a process of runaway accretion in which they rapidly accrete the surrounding gas in an annular feeding zone. In this view, the terrestrial planets Mercury, Venus, Earth and Mars are planetary embryos which never reached the critical mass to accrete the gas from the primordial disk, while Uranus and Neptune only reached critical mass after Jupiter and Saturn and so had their accretion processes altered by gravitational interactions with these giant planets.

Despite being able to form both terrestrial and gas planets, this picture of solar system formation has several weaknesses. The first problem is that core accretion might not act quickly enough to form the planets before the debris disk has been removed. Studies have shown that most young stars lose their gas disks in less than 10\(^6\) years so that core accretion might only be effective in dust

\(^1\)For a catalog of extra-solar planets see http://www.obspm.fr/encycl/catalog.html
Figure 1.1: The orbits and masses of known extra-solar planets. $M_J$ refers to the mass of Jupiter. Figure created and maintained by California and Carnegie Planet Search (http://www.exoplanets.org).
1.1. THE FORMATION OF THE SOLAR SYSTEM

disks around older more isolated stars where the disk would be longer lived (Boss, 2002). Another significant problem is that metre-sized planetesimals experience inward orbital drift due to gas drag which, for objects at 1 AU from the Sun, would pull them into the Sun on a timescale of $\sim 100$ years.

---

![Diagram of core accretion and disk instability](image_url)

Figure 1.2: Sketch of the core accretion scenario (top) and the disk instability model (bottom) for planet formation with approximate time scales. (Boss, 2002)

The main alternative mechanism to core accretion is dynamical instability. In this regime, dynamical instabilities in a sufficiently massive protoplanetary disk rapidly fragment the disk into trailing spiral arms filled with clumps of material. These clumps are tidally stable and rapidly form both a gas envelope and, by sedimentation, a solid core. This process could create a gas giant planet within $10^3$ years and a core of $6M_\oplus$. Here it is assumed that all but hydrogen and helium are subject to sedimentation and that there are no problems forming Jupiter-type
planets before the protoplanetary disk has been removed. In this picture the terrestrial planets are gas giant cores which have had their atmospheres removed either by some form of tidal stripping during a period of orbital migration or by photoevaporation.

However dynamical instability is not without its own difficulties. A dynamical instability regime may require a mechanism such as episodic accretion of gas onto the disk or a close encounter with another star to trigger the production of clumps. Also, it is unclear how massive a planetary core could be created out of dust grains, particularly if the temperatures inside the planetary embryo are high enough for elements such as water to remain as a gas.

The EKB provides a stringent test of both planetary formation models since for any model to be valid it must account for the mass and size of the TNO population. Current observations put the outer radius of the Solar System beyond 150 AU which is comparable to many extra-solar debris disks (Backman and Paresce, 1993; Artymowicz, 1997). Hence, understanding the role of TNOs in the formation and evolution of the solar system may also provide a link to formation of planets around dusty young stars.

The EKB also contains some of the least thermally processed material in the solar system and so may provide the best measure of the composition and mass of the solar nebular which formed the sun and the planets.

1.2 The Search for Pluto

The discovery of Uranus by William Herschel in 1781, and of Neptune by John Adams and Urbain Leverrier, in 1846, lead to widespread speculation both from astronomers and the public that the outer solar system contained more planets.

While several astronomers claimed up to 10 planets remained to be found only two serious predictions from William Pickering and Percival Lowell were made. Pickering used a graphical analysis of the known planets and comets to predict the existence of a planet at 51.9 AU with twice the mass of the Earth (1928). Several surveys were carried out at the predicted position but no new planet was discovered.

Percival Lowell on the other hand determined an orbit for a new planet based on the apparent discrepancies in Neptune's orbit in much the same way that Neptune itself had been discovered. Lowell's 'planet X' was predicted to have a semi-major axis of 43 AU and a mass of 6$M_\oplus$. Lowell was so confident of his prediction that he dedicated his own observatory and almost all of his time to the project. He and others searched for this planet from 1913 until Lowell died suddenly of a stroke on November 12th 1916. The greatest disappointment in his life was his failure to find this planet. In later reviews of the more than 1000 photographic plates taken by Lowell, there were 515 asteroids, 700 variable stars, and 2 images of Pluto which both went unrecognized.

Eventually the task fell to a young farm boy from Kansas, Clyde Tombaugh. He started work at Lowell Observatory in April 1929, almost 13 years after the last serious planet search. On January 23rd and 29th 1930, Tombaugh exposed the pair of plates which upon examination on February 18th, contained Pluto.
By then Tombaugh had examined hundreds of plate pairs sifting through millions of stars.

It was soon realized however that Pluto could not be the much sought after Planet X as it was much too small. Tombaugh continued his search for more than a decade, examining 90 million images of over 30000 square degrees of sky, and found no new planets apart from Pluto. Tombaugh knew that with his telescope he could have discovered a Neptune-sized planet 7 times further away from the Sun than Pluto, or a Pluto-sized planet out to 60 AU, which led him to conclude that no unknown planet brighter than $m_R \sim 16.5$ existed in the Solar System (Tombaugh, 1929).

1.3 The first Trans-Neptunian Object

In the early 1950's, in the midst of several unsuccessful surveys for new planets, two astronomers, Kenneth Edgeworth and Gerald Kuiper (Figure 1.3), who had both worked on the dynamics of asteroids and comets, independently argued that there was no physical justification for the primordial dust disk to have suddenly ended at Neptune (Edgeworth, 1949; Kuiper, 1951). Instead, they theorized that a population of smaller bodies, the remnants of planet formation, could exist in the outer Solar System.

![Figure 1.3: Gerald Kuiper (left) and Kenneth Edgeworth (right) theorized the existence of a belt of objects in the outer Solar System by arguing that there was no basis for the protoplanetary debris disk to have an edge at Neptune.](image)

The first direct evidence of a population of small bodies in the outer solar system came almost 40 years after Edgeworth and Kuiper's original predictions. On November 1st 1977, Charles Kowal after comparing photographic plates taken on the 122cm Schmidt telescope at Palomar Observatory, discovered one new body orbiting at 13.7 AU from the Sun and only a fraction the size of the Earth.
This object, which became known as Chiron, was too small to be considered a planet and instead was the first detection of a population of small bodies named Centaurs (Kowal et al., 1979). However, the discovery of such a population was thought to be theoretically impossible, as Centaurs orbit in the chaotic region between Jupiter and Neptune and thus could not have survived for the age of the solar system.

At the time another population of solar system bodies was also presenting several contradictions. While comets had been seen since prehistoric times, it wasn’t until 1950 when Jan Oort proposed that these small icy bodies came from a spherical shell of dust and debris at the edge of the Sun’s gravitational influence, about halfway to the nearest star. He theorized that these small bodies spent most of their life in the ‘Oort cloud’ until collisions caused by galactic tides perturbed them into solar system crossing orbits (Oort, 1950). In this scenario, comets should all have relatively long periods (~200 years) and uniformly distributed orbital elements reflecting their random distribution within the cloud. However in the following decade the number of known comets rose to over 200, and of this population, more than 30% were on prograde orbits with periods between 3.3 and 13 years, semi-major axes < 8 AU and a median inclination of 10°. The presence of this population, known as ‘short-period’ or ‘Jupiter-family’ comets suggested significant problems with the current picture of the outer solar system.

One hypothesis to explain these short-period comets was that they had evolved from long period comets through successive moderate perturbations by Jupiter and the other planets (Kazimirchak-Polonskaya, 1972). However, several simulations concluded that the rate of such evolution is not sufficient to produce the large fraction of short-period comets observed (Kresak and Pittich, 1978; Yabushita, 1979). Instead several astronomers suggested that a reservoir of objects beyond Neptune could serve as the source of Jupiter-family or short-period comets (Whipple, 1964; Duncan et al., 1988; Quinn et al., 1990; Fernandez and Gallardo, 1994).

Another indirect argument for the existence of debris in the outer solar system came from observations of dust disks surrounding nearby stars such as β Pictoris (Vidal-Madjar et al., 1998). Almost all observed young stars are found to have dusty disks which extend to distances of hundreds of AU. These dust disks are thought to be the progenitors of planetary systems (Fischer and Pfau, 1997; Ozerney et al., 2000; Greaves et al., 2004). Since our own solar system is thought to originate from a similar debris disk, it was argued that perhaps the outer solar system contained the remnants of a similarly extended debris disk (Irwin et al., 1995).

With mounting circumstantial evidence that the outer solar system was not as barren as once thought, in 1987 and again in 1988, Dr David Jewitt and his then student Jane Luu conducted surveys using photographic plates covering a few hundred square degrees of sky, but both were unsuccessful in detecting new objects (Luu and Jewitt, 1987; Luu and Jewitt, 1988).

In 1992 Jewitt and Luu had the opportunity to use the 2.2m telescope on Mauna Kea which had recently had its photographic plates replaced with CCD’s. This new system of collecting photons had a much greater quantum efficiency and the advantage of creating a digital image.
On August 30 and again the following night they discovered a faint slow-moving object (shown in Figure 1.4), which by its apparent angular velocity, was in orbit beyond Neptune. This new object, known as 1992 QB$_1$, in the nomenclature for recording asteroids, had an apparent magnitude of $m_R \sim 22.8$ and, based on the assumption of a circular orbit, a semi-major axis of 42 AU and an inclination of 2.3° (Jewitt et al., 1992; Jewitt and Luu, 1993).
1.4 The Edgeworth-Kuiper Belt

The object discovered by Jewitt and Luu, 1992 QB₁, soon became the first detection of a population of small icy bodies known as Trans-Neptunian Objects or TNOs, which orbit the Sun beyond Neptune in a region which has become known as the Edgeworth-Kuiper belt (EKB) after the two astronomers who predicted it's existence. It has been theorized that the region contains approximately 10⁵ small icy bodies larger than 50 km in diameter (Jewitt and Luu, 2000) making it the ideal reservoir of both Centaurs and short-period comets. The EKB is also thought to extend out to more than 100 AU and possibly as far as the Oort cloud which would make it of comparable size to many circumstellar disks observed around nearby young stars.

Figure 1.5: In our current understanding of the outer solar system, long period comets (red) are thrown into the solar system from the Oort cloud because of galactic tides while the short period comets (blue) originate in the EKB and are perturbed onto orbits which take them into the solar system by interactions with the planets.
Currently more than 800 TNOs have been discovered and recorded at the Minor Planet Center\(^2\). Most of these objects have fallen into 3 distinct categories, Classical TNOs, Resonant TNOs and Scattered TNOs. These groups are shown in Figure 1.6 along with several other classes of minor planets.

Figure 1.6: Plot of the outer Solar System prepared by the Minor Planet Center 28 September 2004. The orbits of Jupiter through Neptune are shown as light blue rings while the planets themselves are shown as blue circles with a cross in the centre. Pluto is marked as a white circle with a cross. Cyan triangles represent objects with high eccentricity, orange triangles represent the Centaur population. Comets are shown as light blue squares where filled squares denote numbered periodic comets and all other comets are denoted by unfilled squares. White circles indicate the resonant TNOs, red circles denote the classical TNOs and magenta circles represent the scattered TNO population. Note: for the TNOs, the filled circles indicate objects which have been observed at more than one opposition and unfilled circles represent those objects which have only been observed at one opposition.

\(^2\)http://cfa-www.harvard.edu/iau/mpc.html
1.4.1 Classical TNOs

Classical TNOs are so called because they orbit close to the invariable plane\(^3\), the region where it was first thought all TNOs would exist. Classical TNOs account for more than 60% of the observed TNO population and were initially thought to be dynamically cold, with flat nearly circular orbits, orbiting the Sun with semi-major axes between 40 and 60 AU. These TNOs also appear to be dynamically stable over the lifetime of the solar system (Holman and Wisdom, 1993; Duncan et al., 1995; Morbidelli et al., 1995).

![Histograms of semi-major axis, inclination and eccentricities of all classical TNOs having multi-opposition observations.](image)

Figure 1.7: Histograms of the semi-major axis, inclination and eccentricities of all classical TNOs having multi-opposition observations.

Further discoveries, however, have produced some surprises. The surface density of the Classical EKB is only a fraction of that expected from a smooth extrapolation of the surface density derived from the mass in the inner solar system (Weidenschilling, 1977). It is also 2 orders of magnitude less than the amount

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\(^3\)The invariable plane is the place through the centre of mass of the solar system perpendicular to the angular momentum of the solar system, and it represents the location where the debris disk initially settled before forming all the objects in the Solar System. This plane is inclined at 1.6° to the ecliptic.
of matter required to form the largest known TNOs within $10^5$ years, after which
time perturbations from the giant planets would have halted the growth of large
bodies (Stern, 1996; Stern and Colwell, 1997; Kenyon and Luu, 1999).

Another feature of the known classical population is the apparent narrow
range of semi-major axes. As shown in Figure 1.7, all classical TNOs have a semi-
major axis between 40 and 48 AU. Within 50 AU, the gravitational influence of the
giant planets could be responsible for depleting the region (Holman and Wisdom,
1993; Levison and Duncan, 1993; Duncan et al., 1995). However, beyond 50 AU,
the impact of the giant planets on the EKB would be minimal and so expected
to reflect the primordial surface density of objects (Hahn and Malhotra, 1999).

However, after a decade of observations no classical TNO has been observed
with a semi-major axis $> 50$ AU as shown in Figure 1.7. Closest to this edge
is 2000 $AF_{255}$ a TNO with a predicted semi-major axis between 46.2 and 49.3
AU (Gladman et al., 2000). The lack of detections beyond 50 AU has lead some
investigators to claim that 50 AU marks the edge of the classical EKB (Allen
et al., 2001). Statistical tests of this edge have found that while it’s existence
is dependent on the assumed size and radial distribution of TNOs, it is not the
result of observational bias (Allen et al., 2001; Gladman et al., 1998).

Several explanations exist for this paucity of objects. One plausible reason
for the lack of detections is that the primordial debris disk did not extend further
than 50 AU (Jewitt et al., 1998; Chiang and Brown, 1999). If Uranus, Neptune
and the EKB formed much closer to the Sun than their present position and the
planets migrated to their present positions, the EKB may have been similarly
displaced (Malhotra, 1993; Malhotra, 1995; Allen et al., 2001).

Ida, Larwood and Burkett (2000) propose the presence of a nearby star during
the final stages of planet formation may have dynamically excited the EKB and
halted planetesimal growth in the outer solar system. This scenario is further
supported by arguments that the Sun formed in a cluster of stars where a stellar
encounter would be much more likely (Adams and Laughlin, 2001).

Another theory is that 1 or 2 Earth-mass bodies beyond 50 AU could also
disrupt the formation of more distant TNOs (Fernandez, 1980). Such excitation
could have increased the eccentricities and inclinations of the classical TNOs,
lowering the apparent surface density on the sky (Allen et al., 2001).

It has also been conjectured that the physical properties of classical TNOs
beyond 50 AU are different from known classical TNOs. TNOs in the outer solar
system could be significantly fainter, due to a lower albedo, redder colour or
smaller size and, in these cases, could have escaped detection by previous surveys
(Allen et al., 2001).

As well as the lack of classical TNOs beyond 50 AU, the second surprise
has been the recent discoveries of classical TNOs with inclinations up to $30^\circ$,
shown in the centre plot in Figure 1.7. (Jewitt and Luu, 1995; Jewitt et al.,
1996; Jewitt et al., 1998; Trujillo et al., 2001a; Trujillo et al., 2001a). There has
been some debate that the classical EKB is made up of 2 distinct populations,
one of which is dynamically cold and resides in the invariable plane (Hahn and
Malhotra, 1999: Allen et al., 2002) while the other is dynamically warm. This
warm population of TNOs appears to have a median inclination of $17^\circ$ (Trujillo
et al., 2001a; Brown, 2001) while the cold TNO population have inclinations $< 5^\circ$. 


Further, Levison and Stern (2001) conjecture that a correlation exists between a TNOs inclination and its absolute magnitude such that the warm Classical TNO population also contains the brightest, largest TNOs. However this theory is yet to be substantiated, as it suffers from small number statistics because the bulk of surveys have been conducted in the Ecliptic where inclined objects spend preferentially less of their orbit.

1.4.2 Resonant TNOs

Resonant TNOs are so named because they orbit in one of Neptune's resonances. Resonant TNOs make up ~ 40% of the known population of TNOs the largest and best known of which is Pluto in the 3:2 resonance, which means that for every time Neptune orbits the Sun three times, Pluto will orbit the Sun twice. This is the reason TNOs in the 3:2 resonance are commonly known as plutinos. Resonant TNOs are protected from collisions with Neptune which is why they can safely cross Neptune's orbit. This can be seen in the plot of the outer solar system shown in Figure 1.6, where several of the white circles denoting resonant TNOs are inside the light blue ring of Neptune's orbit. As shown in Figure 1.9, while almost all other resonances are populated, the 3:2 resonance contains the most objects.

![Figure 1.8: The distribution of eccentricity versus semi-major axis for both classical and resonant TNOs. Filled circles represent TNOs with multi-opposition orbits, open circles to single-opposition orbits. The dashed line denotes perihelion, q = 30 AU, where TNOs lying above this line are Neptune crossers. The bands of dotted lines indicate Neptune's mean motion resonances (Malhotra, 1996).](image-url)
As shown in Figure 1.9, resonant TNOs have eccentricities up to 0.4 and inclinations as large as 35° which are the result of their interaction with Neptune. They also have semi-major axes between 37 and 42 AU.

Figure 1.9: Histograms of the semi-major axis, inclination and eccentricities of all resonant TNOs having multi-opposition observations.

One explanation for the relatively large number of TNOS trapped in resonance with Neptune, put forward by Malhotra (1993; 1995), is that it is the result of the outward migration of Neptune during the latter stages of planetary formation. In this scenario Jupiter, Saturn, Uranus and Neptune all formed relatively close together several AU from the Sun. Then, once Jupiter and Saturn were large enough, they began to migrate inwards to their present positions. Due to the conservation of momentum, this caused Uranus and Neptune to be pushed outward and during this outward migration Neptune could 'sweep up' a large number of objects into its resonances. However this theory predicts that the 3:2 and 2:1 resonances be filled equally but, as shown in Figure 1.8, the 2:1 resonance is a factor of 4 less populated than the 3:2 resonance.
1.4.3 Scattered TNOs

Scattered TNOs make up less than 10% of the known TNOs, but this is believed to be the result of observational bias rather than a true reflection of the entire population. On the contrary, there is speculation that the scattered TNOs could be the largest population in the EKB. As shown in Figure 1.10, scattered TNOs are difficult to detect because they have extreme orbits such as semi-major axes of more than 250 AU, eccentricities which range from 0.25 to 1 and inclinations typically larger than 10° which places them at great distances from the Sun for the bulk of their orbits (Trujillo et al., 2000).

![Figure 1.10: Histograms of the semi-major axis, inclination and eccentricities of all scattered TNOs having multi-opposition observations.](image-url)

This population is thought to have originally consisted of classical and resonant TNOs which were scattered onto highly eccentric and inclined orbits as a result of interactions with Neptune. As such, it was expected that all scattered TNOs would have perihelia around 35 AU, however several new scattered TNOs have very different perihelia. Gladman et al. (Gladman et al., 2002) found two distant TNOs, the first was TNO 1995 TL₈ which had a perihelion of ~40 AU.
while the second, TNO 2000 \( CR_{105} \) was measured with a perihelion of \( \sim 44 \) AU which led them to speculate about the existence of a densely populated ‘extended’ scattered disk. Recently Brown and Trujillo announced the discovery of Sedna (Brown et al., 2004b), currently the most distant solar system object with a semi-major axis of \( 480 \pm 40 \) AU and a perihelion of \( 76 \pm 4 \) AU, which they theorize is the first detection of an inner Oort cloud.

## 1.5 Large TNOs

The population of TNOs with radius > 500km represent ideal candidates for studying the physical and chemical properties of the outer solar system as these objects are bright enough that they are accessible from both ground and space based observatories with a host of instruments. However the current known population of large TNOs suffers from several drawbacks.

One trait lacking from the current TNO population is small number of objects which have a measured albedo. Instead the common practice is to assume an albedo of 0.04, a value which is typical for comets. However, detailed studies have shown that TNOs display a wide range of albedos which directly affects inferences about their diameter. Large TNOs are bright enough to obtain both thermal and visible measurements which can be combined to break the degeneracy between TNO albedo and diameter.

Such TNOs are also large enough to be directly imaged by the HST which allows for direct analysis of the changing surfaces of these objects as they rotate. Such analysis has been performed on Pluto (Stern and Colwell, 1997) resulting in a better understanding of the planets change in magnitude with rotation. These TNOs also offer more chances for occultations and longer duration events. Occultations have been observed for Chiron (Elliott, 1995; Bus et al., 1996), Charon (Walker, 1980; Elliot and Young, 1991) and Pluto (Elliott et al., 1989; Millis et al., 1993a) enabling analysis of their atmospheres.

From a theoretical point of view, the number of large TNOs is important because it directly measures the rate of accretion during the formation of the planets (Kenyon and Luu, 1998). Of particular interest are the number of Charon-sized bodies (radius \( \sim 500 \) km) and the number of Pluto-sized bodies (radius \( \sim 1000 \) km) (Trujillo et al., 2001a). A detailed accretion model of the early EKB by Kenyon and Luu (1999) demonstrates that several Pluto-sized objects could form within the age of the solar system.

There also remains an open question as to whether the mass of the EKB is tied up in the largest or smallest objects (Chiang and Brown, 1999). Determining the bright end of the TNO size distribution is the easiest way to answer this question.

As shown in Table 1.1, presently only a handful of large TNOs have been detected. This is because at the ecliptic, TNOs brighter than \( m_R < 20 \) have a surface density of about 1 TNO/100 deg\(^2\) and so to finding these objects requires that a significant portion of the sky must be covered. To date more than 1000\( deg^2\) has been surveyed down to a magnitude \( m_R \sim 20 \) but this has primarily been focused on the ecliptic. There is building evidence that TNOs orbit at a large
TABLE 1.1: The Radius and Albedo measured for the largest known TNOs

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<th>Albedo</th>
<th>Reference</th>
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<td>Pluto</td>
<td>1185-1200</td>
<td>0.44-0.61</td>
<td>(Millis et al., 1993b)</td>
</tr>
<tr>
<td>2003 VB₁₂</td>
<td>~800</td>
<td>0.04</td>
<td>(Brown et al., 2004b)</td>
</tr>
<tr>
<td>2004 DW</td>
<td>~800</td>
<td>0.04</td>
<td>(Brown et al., 2004a)</td>
</tr>
<tr>
<td>50000 Quaoar</td>
<td>630 ± 95</td>
<td>0.093 ± 0.023</td>
<td>(Brown and Trujillo, 2004)</td>
</tr>
<tr>
<td>20000 Varuna</td>
<td>450 ± 65</td>
<td>0.070 ± 0.017</td>
<td>(Jewitt et al., 2001)</td>
</tr>
<tr>
<td>19308 1996 T066</td>
<td>&lt; 449</td>
<td>&gt; 0.04</td>
<td>(Altenhoff et al., 2004)</td>
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<tr>
<td>55565 2002 AW197</td>
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<td>0.101 ± 0.038</td>
<td>(Margot et al., 2002)</td>
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<tr>
<td>28978 Ixion</td>
<td>&lt; 402</td>
<td>&gt; 0.15</td>
<td>(Altenhoff et al., 2004)</td>
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</tbody>
</table>

a also known as Sedna.
b Assumed albedo.

range of latitudes and that the discovery of one or more Pluto-like objects waits only for regions away from the ecliptic to be observed.

1.6 Past Surveys

Since the discovery of the first TNO, 1992 QB₁, many surveys have been carried out with the aim of determining not only the characteristics of the EKB’s population but also to make inferences about its formation and evolution.

There are two main strategies one can use in order to look for a population of outer solar system objects. The goal of the first method is to maximise the number of TNO detections by observing a small area with a long exposure and recording every object which passes through that area. Survey’s of this type are known as ‘pencil-beam’ surveys.

The second survey strategy is to attempt a wide area search with a relatively shallow depth in the hopes of detecting rare large TNOs. As most TNO surveys are constrained by the faintness of the TNOs and the limited use of telescope time, they choose the first search method but this results in a known population made up almost entirely of small, faint objects with poorly constrained orbits because each object is observed for only a short period of time. Another drawback is that information is only known about a very small area of sky. As a result, the present state of the TNO population provides very little insight into the overall characteristics of the EKB.

Recently, more emphasis has been put on surveys using the second search strategy. With more wide-area cameras being built for telescopes, surveying the entire night sky on a regular basis will soon become a reality. The advantage of such a strategy is that objects can be observed at multiple points in their orbit, bright objects which could contain the bulk of matter in the region would be easily detected and a large population of TNOs could be quickly built up. A summary of previous surveys is shown in Table 1.2.
Table 1.2: A table of previous surveys

<table>
<thead>
<tr>
<th>Survey</th>
<th>Sky Coverage ($deg^2$)</th>
<th>Limiting Magnitude $m_{R50}$</th>
<th>TNOs Detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Tombaugh, 1929)</td>
<td>~19500</td>
<td>15.5</td>
<td>1</td>
</tr>
<tr>
<td>(Kowal et al., 1979)</td>
<td>6400</td>
<td>18.5</td>
<td>0</td>
</tr>
<tr>
<td>(Luu and Jewitt, 1988)</td>
<td>297</td>
<td>19.5</td>
<td>0</td>
</tr>
<tr>
<td>(Levison and Duncan, 1990)</td>
<td>4.9</td>
<td>21.0</td>
<td>0</td>
</tr>
<tr>
<td>(Cochran et al., 1995)</td>
<td>0.0011</td>
<td>28.6</td>
<td>29</td>
</tr>
<tr>
<td>(Irwin et al., 1995)</td>
<td>0.7</td>
<td>23.5</td>
<td>2</td>
</tr>
<tr>
<td>(Irwin et al., 1995)</td>
<td>50</td>
<td>20.0</td>
<td>0</td>
</tr>
<tr>
<td>(Williams et al., 1995)</td>
<td>0.5</td>
<td>22.0</td>
<td>1</td>
</tr>
<tr>
<td>(Jewitt and Luu, 1995)</td>
<td>1.2</td>
<td>24.8</td>
<td>7</td>
</tr>
<tr>
<td>(Jewitt et al., 1996)</td>
<td>3.9</td>
<td>24.2</td>
<td>12</td>
</tr>
<tr>
<td>(Jewitt et al., 1996)</td>
<td>4.4</td>
<td>23.2</td>
<td>3</td>
</tr>
<tr>
<td>(Brown and Webster, 1998)</td>
<td>12</td>
<td>21.0</td>
<td>0</td>
</tr>
<tr>
<td>(Jewitt et al., 1998)</td>
<td>51.5</td>
<td>22.5</td>
<td>13</td>
</tr>
<tr>
<td>(Luu and Jewitt, 1998)</td>
<td>1007</td>
<td>26.1</td>
<td>5</td>
</tr>
<tr>
<td>(Trujillo and Jewitt, 1998)</td>
<td>2.22</td>
<td>23.1$^a$</td>
<td>2</td>
</tr>
<tr>
<td>(Chiang and Brown, 1999)</td>
<td>0.01</td>
<td>27.9</td>
<td>2</td>
</tr>
<tr>
<td>(Sheppard et al., 2000)</td>
<td>1428</td>
<td>18.8</td>
<td>0</td>
</tr>
<tr>
<td>(Trujillo et al., 2001a)</td>
<td>164</td>
<td>21.1</td>
<td>3</td>
</tr>
<tr>
<td>(Larsen et al., 2001)</td>
<td>522</td>
<td>20.0</td>
<td>7</td>
</tr>
<tr>
<td>(Trujillo et al., 2001b)</td>
<td>73</td>
<td>23.7</td>
<td>86</td>
</tr>
<tr>
<td>(Ferrin et al., 2001)</td>
<td>67</td>
<td>20.1</td>
<td>1</td>
</tr>
<tr>
<td>(Allen et al., 2001)</td>
<td>1.3</td>
<td>24.9</td>
<td>23</td>
</tr>
<tr>
<td>(Ivezić et al., 2001)</td>
<td>500</td>
<td>21.5</td>
<td>1</td>
</tr>
<tr>
<td>(Millis et al., 2002)</td>
<td>76.7</td>
<td>23.9</td>
<td>69</td>
</tr>
<tr>
<td>(Bernstein et al., 2004)</td>
<td>0.02</td>
<td>29.2</td>
<td>3</td>
</tr>
</tbody>
</table>

$^a$ Visual plus Red limiting magnitude
1.7 The Southern Edgeworth-Kuiper belt Survey

In this thesis I present the aims, results and conclusions of the Southern Edgeworth-Kuiper belt (SEK) Survey. This survey was designed to have large sky coverage, uniform and well defined detection limits, and bi-colour observations making it ideal for the detection and recovery of bright TNOs. It is also the largest of its kind carried out in the southern hemisphere.

In chapter 2 of this thesis I discuss the aims and methodology of the Survey including a detailed description of the telescope, the synthetic population created to analyse the detection efficiency, and the observing and recovery strategies as well as a statistical analysis of the data.

Chapter 3 covers the fully automated data reduction pipeline designed to take full advantage of the unique features of the survey, including the search algorithm and orbit determination software developed for selecting TNOs from the data.

In Chapter 4 I present the TNO and Centaur candidates discovered by the Survey and also the TNOs serendipitously recovered in the survey observations.

Chapter 5 uses the candidates found by the survey to probe some of the EKB’s remaining open questions. It includes a discussion on the TNO detection efficiency of the survey along with our calculation of the Cumulative Luminosity Function (CLF) at the bright end with a comparison to the CLF as determined by past Surveys. It also details the surveys sensitivity of detecting Centaurs and the resulting Centaur CLF. Also in this chapter the issue of TNO and Centaur colour is examined.

The final chapter states the main conclusions resulting from this survey and the avenues for future research.
Chapter 2

The Survey

"In the fields of observation chance favours only the prepared mind."
Louis Pasteur

2.1 Introduction

A survey aiming to create a comprehensive inventory of the outer solar system should have large sky coverage, a faint limiting magnitude, uniform and well-defined detection limits in magnitude and proper motion, accurate multi-colour photometry for taxonomy, and sufficient follow-up observations in order to obtain well determined orbits (Ivezić et al., 2001). The Southern Edgeworth-Kuiper belt survey was created to meet all of these aims with the exception of a relatively bright limiting magnitude. The goal of the survey was to cover a significant fraction of the ecliptic in two colours and also observe fields up to 20 degrees from the ecliptic, while also developing a self-consistent method of determining the Survey’s detection efficiency, which will result in a sample of bright TNOs which could be utilized for other studies.

The survey began on January 1, 2000 and survey observations were taken until January 18, 2003 when the Mount Stromlo Observatory was devastated by fire. The fires not only destroyed the Great Melbourne telescope which was being utilized for the SEK survey, but were also responsible for the loss of the Survey’s computers which were also housed in the telescope dome. These computers contained the data reduction software and the 80% of the survey data which had been reduced to that point. Luckily, while the setback to the survey was significant it was not catastrophic as the raw survey observations were stored off site and were not affected by the fires.

At the time, Mount Stromlo Observatory had no facilities for re-processing the data on site so Professor Charles Alcock and the University of Pennsylvania generously offered the use of their computing facilities. Dr Brian Schmidt copied all the compressed raw data onto three 400 G firewire disks and shipped to the US along with the data reduction software, while with the assistance of almost the entire astronomy department at the University of Pennsylvania, the software was modified to work on a different platform and separated into sections in order to utilize several machines at once. With all of this assistance and a great deal of
2.2. The Telescope and Camera System

All SEK Survey observations were taken using the Great Melbourne Telescope (GMT) located at the Mount Stromlo Observatory. This telescope was uniquely suited to a large sky search for TNOs because it had a wide field of view and it was fitted with a dual-camera system. Another advantage of this telescope was that a minimum of 80% of the telescope time was allocated to the survey.

Previously utilized for the MACHO project (Alcock et al., 2000 and references therein), the telescope comprised a 50 inch aperture paraboloidal primary mirror, with a corrected field of view of 0.5 deg² at prime focus. The telescope was built with a ‘Modified German Mount’ which enabled large areas to be observed from both the east and west side of the mount axis (Hart et al., 1996).

The telescope had a wide-field prime-focus corrector which incorporated a dichroic element to allow simultaneous imaging in two colors onto two CCD cameras (Hart et al., 1996). The ‘red’ passband spanned 6300-8100 Å while the ‘blue’ spanned 4500-6300 Å. These two passbands are non-standard and their approximate response is shown in Figure 2.1 where the standard passbands (Bessell, 1990) are included for comparison.

Each camera system comprised four 2048x2048 pixel, unthinned ‘edge-butttable’ Loral CCDs, which were cooled cryogenically (Stubbs et al., 1993) and had a scale of 0.625 arcsec/pixel in the red and 0.631 arcsec/pixel in the blue. The chips also had a different orientation depending on which side of the mount axis an observation was taken (Figure 2.2). Each CCD was read out through 2 amplifiers creating 16 images each with an independent bias level and flat-field response. The readout time was 67 seconds per image and the noise was ~10 electrons rms with a gain of ~1.9 e⁻/analog-to-digital unit (ADU) (Alcock et al., 1999).

Prior to June, 2001 the telescope was operated by 2 part-time paid observers. After this time the telescope was taken off-line for 2 months in order to implement upgrades to the telescope to make it fully automated. This was achieved by the addition of Cryotiger closed-circuit coolers, to obviate the need for liquid nitrogen filling twice a night: implementing software to undertake the previously human tasks of pointing calibration, focusing, weather monitoring, telescope dome opening and closing and observation scheduling; and building of a small on-site weather station directly connected to the telescope.
Figure 2.1: Approximate instrumental throughput for the blue and red camera (Bessell and Germany, 1999). A throughput of 1 would indicate no loss of light; wavelength is in nm. Also shown are the standard BVRI passbands from Bessel (1990).
Figure 2.2: Schematic drawing of the camera focal plane (red, *left*; blue, *right*) in the east of pier (*top*) and west of pier (*bottom*) orientation. CCD-amplifier combinations are labeled (Alcock et al., 1999).
2.3 A Synthetic Data Set

One of the most important goals of any survey is to put their survey results in context by having a complete understanding of the intrinsic biases and detection efficiency of the survey. The determination of these biases is commonly undertaken during the final stages of a survey with the main focus of measuring the depth of magnitude intrinsic to each observation. However there are many other factors besides magnitude which influence why moving objects are detected or lost and so concentrating on only the limiting magnitude will give a less realistic measurement of the Survey’s sensitivity to detecting TNOs.

Our aim was to include all the factors influencing the detection of a moving object in our calculation of the Survey’s detection efficiency so that it would be a true reflection of the TNO population rather than the Survey biases. This measurement was also designed to be done in real time so that the statistics of a field, a night’s observations or the entire survey could be calculated which would enable changes to be made to the analysis pipeline to improve the detection efficiency if required.

Our strategy was to generate a synthetic population of $10^9$ objects defined to encompass both known and new exotic distant solar system bodies. Using this dataset, various aspects of the observing strategy, data pipeline and overall survey biases could be investigated.

The synthetic dataset created for the survey was defined by 11 parameters. The first six parameters were the semi-major axis, inclination, eccentricity, argument of perihelion, longitude of ascending node and mean anomaly which define the orbit of each synthetic body. As shown in Table 2.1, the semi-major axis parameter is uniformly sampled from between 10 and 110 AU while the remaining parameters uniformly sample the entire range of parameter space. By sampling such a wide range of the parameter space the synthetic bodies encompass the properties of known classical, resonant and scattered TNOs but also include the possibility of as yet undiscovered TNO populations.

The seventh parameter is a randomly chosen diameter uniformly sampled from between 1km and 1200km to encompass the typical sizes of known TNOs up to approximately the size of Charon. The eighth parameter is a colour (B-V) offset which is selected from a Gaussian distribution centered on B-V of 0.5. This distribution was chosen to reflect the expectation that TNOs, due to their dusty surface would reflect more red light than blue (Luu and Jewitt, 1996), but also to include synthetic objects which have neutral or even faintly blue colours since similar TNOs have also been detected (Barucci et al., 2000).

All synthetic objects are assumed to have an albedo of 0.04 and this is given in parameter 11. This is a common assumption since few TNOs are too faint for current albedo measurements and comets are typically known to have albedo’s of this order. While several larger TNOs have been found with much higher albedos (see Table 1.1), this assumption does not greatly affect the synthetic population since the diameter and albedo are degenerate in the brightness calculation.

Based on earlier work suggesting that TNOs can vary in their brightness (Hainaut et al., 2000; Jewitt and Sheppard, 2002) the final 2 parameters defining the synthetic population explore this possibility. All synthetic objects are
2.3. A SYNTHETIC DATA SET

assumed to vary in magnitude sinusoidally with a period of six hours. Then, one third of all objects are selected to vary with an amplitude of 0. that is, they are assumed to have a constant brightness; one third are selected to vary by 0.4 magnitudes while the remaining third have an amplitude of variation of 0.8 magnitudes. These values were chosen to encompass the variation seen in TNOs such as Varuna (Jewitt and Sheppard, 2002) and 1998 SN 165 (Peixinho et al., 2002). These 11 parameters are summarized in Table 2.1.

Table 2.1: The parameters defining the synthetic population.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-major Axis</td>
<td>10-110 AU</td>
</tr>
<tr>
<td>Inclination</td>
<td>0 - 180°</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0-1</td>
</tr>
<tr>
<td>Argument of Perihelion</td>
<td>0 - 360°</td>
</tr>
<tr>
<td>Longitude of Ascending Node</td>
<td>0 - 360°</td>
</tr>
<tr>
<td>Mean Anomaly</td>
<td>0 - 360°</td>
</tr>
<tr>
<td>Diameter</td>
<td>1-1200 km</td>
</tr>
<tr>
<td>B-V colour</td>
<td>-0.1-1</td>
</tr>
<tr>
<td>Albedo</td>
<td>0.04</td>
</tr>
<tr>
<td>Period of brightness variation</td>
<td>6 hrs</td>
</tr>
<tr>
<td>Amplitude of brightness variation</td>
<td>0.0.4-0.8 mag</td>
</tr>
</tbody>
</table>

In order to use this dataset, the position and brightness of each synthetic object must be able to be calculated for any given time. The position and radial distance for a synthetic body at a given time is calculated using a SLAlib (Wallace, 1994) routine, slaPlante, modified to output the position in J2000 coordinates. Then the constant red magnitude of each synthetic body is calculated with the equation

\[
m_{R_c} = m_{R_\odot} - 2.5 \log_{10} \left( \frac{pd^2}{2.25 \times 10^{16} R^2 (R - 1)^2} \right), \tag{2.1}\]

where \(m_{R_\odot} = -27.1\) is the magnitude of the sun, the albedo, \(p\), is defined as 0.04. \(R\) is the objects distance from the Sun in AU and \(d\) is the diameter of the object in kilometers (Jewitt and Luu, 1995). To determine the true red magnitude, \(m_R\), this constant magnitude is added to the amount of brightness variation given in parameter 12 such that.

\[
m_R = m_{R_c} + a \sin \left( \frac{2\pi t}{\rho} \right), \tag{2.2}\]

where \(a\) is the amplitude of variation defined as parameter 11. \(t\) is the time in hours since last maximum and \(\rho\) is the period of variation. Once \(m_R\) is calculated, \(m_V\) is given by the equation:

\[
m_V = m_R + (B - V)_{\text{colour}} \tag{2.3}\]

[^1]: http://star-www.rl.ac.uk/star/docs/sun67.htm/sun67.html
where the \((B - V)_{\text{colour}}\), given in parameter 12, is the defined colour of the object.

The advantage of including this synthetic population in our reduction analysis is that it represents an unbiased sample which can be used to probe the proficiency of every step of the observing strategy and the data reduction pipeline.

It is important to emphasize that this dataset does not include objects which lie in the asteroid belt between Mars and Jupiter. The objects in this belt make up the majority of observed moving objects and hence pose a real threat of contaminating our TNO candidates. Instead, the effect of less distant solar system objects on the survey is probed using a subset of real asteroids whose orbits are recorded at the MPC. This population is described in detail in Chapter 3.

2.4 The Observing Strategy

In the past two main techniques have been utilized in the search for slow moving objects. The first technique was to search for TNOs by observing a small area of sky down to the faintest limiting magnitude. These ‘pencil beam’ surveys were designed to maximize the typically limited amount of observing time and the probability of detecting a TNO. The second technique was to survey a large area of sky albeit at the expense of a relatively bright limiting magnitude. The advantage of a pencil beam survey is that large numbers of TNOs can be observed, while the advantage of a wide area survey is that rare, bright TNOs will be detected and they will have sufficiently long arcs to produce orbits typically accurate enough for the object to be easily recovered for more than a decade. The SEK survey is a wide area survey.

2.4.1 Choice of Exposure Time

The choice of exposure time was critical to getting the most out of the Survey. A relatively short exposure time would ensure that a large area of sky could be covered each night and that losses due to cosmic rays, saturated stars, bad pixels and chip boundaries were minimized. A short exposure time would also prevent slow moving objects from appearing trailed in the image and thus being rejected by a reduction pipeline focused on extracting sources with stellar PSFs. However, a longer exposure time would result in greater depth in the observations which would increase the probability of detecting a TNO as smaller, fainter TNOs are exponentially more numerous than large, bright TNOs (Trujillo et al., 2001a).

Another consideration is the mosaic readout time. If the exposures are too short more observing time is spent reading out the CCD than collecting photons.

The reasonable exposure time for our observations was determined to be 300s. Choosing 5 minute exposures allowed objects as faint as \(m_R \approx 20\) to be detected with no trailing and also reduced the chance of slow moving objects moving off the field between observations. The CCDs on the GMT had a readout time of \(\sim 60\) seconds which was fast enough to ensure that by the time that the telescope had moved to the position of the next observation, the readout had been completed.
2.4. THE OBSERVING STRATEGY

2.4.2 Selection of Search Fields

Previous surveys had focused their attention on the ecliptic where, similar to the planets, all solar system bodies were expected to be found. However, new evidence suggests that a relationship exists between an object's magnitude and its inclination which would result in large TNOs with preferentially higher inclinations which would then spend the bulk of their orbit several degrees away from the ecliptic (Levison et al., 2001).

Another consideration was to ensure that regions where known TNOs could be recovered for external validation of the analysis, were included in the survey area while it was also desirable to search previously unobserved territory.

Our observing strategy was to comprehensively cover a 3° wide band centered on the ecliptic and encompassing the bulk of the invariable plane. Once this region had been surveyed, the strategy was to systematically widen this region out to a maximum of 10° from the ecliptic and biased towards more southern latitudes. This strategy was designed to allow the Survey to uniquely quantify the distribution of bright TNOs in the ecliptic while also searching for TNOs at higher inclinations.

2.4.3 Number of Observations

In order to recover a moving object, at least two observations are necessary, but to cover a large area of sky in a limited time, there needs to be an efficient balance between reobserving fields and observing new fields. The observing strategy must also incorporate the need for multiple observations since these observations can be used to provide confirmation of the TNO. Also, several observations taken over a long baseline will further constrain an orbit and reduce the area of sky which must be searched to ensure recovery during follow-up.

It was determined that each field would be observed three times to allow a large area of sky can be quickly covered while still retaining the ability to find TNOs.

2.4.4 Sequence of Observations

The sequence of observations needed to be chosen in order to take into account the motion of a typical TNO. To allow a TNO to be detected, the three observations are required to have a sufficient separation that a TNO in the field would have clearly moved. The apparent angular velocity of a TNO on a circular orbit, at opposition is given by the equation:

$$\dot{\theta} = 148 \left( \frac{1 - R^{-0.5}}{R - 1} \right) \ " / hr \quad (2.4)$$

By this equation, a TNO at 40 AU would have an apparent motion of 3"/hr. For a TNO to be classified as a moving object by the analysis pipeline, the centre of each detection must have moved by at least 2", and so the minimum time between observations is 40 minutes.
The maximum time between observations is influenced by the probability of a TNO moving off a field before the observations are completed. The telescope’s field of view is 40’x40’ and so a TNO will travel an average distance of 20’ before coming to a field boundary. With this constraint the maximum time between observations is 16 days. It’s important to note also that a longer baseline for observations is useful for immediately excluding less distant bodies as TNO candidates, since it is likely such bodies will have moved off the field between observations.

With these constraints in mind, the initial observing strategy was to take the first and second observations separated by a minimum of 4 hours with the third observation taken at least 24 hours later but within 7 days of the initial observation.

This sequence of observations was chosen in order to make use of the orbit fitting code developed by Bernstein and Khushalani (2000). Their code was designed to constrain the possible orbits and thus reduce the number of recovery observations required. This procedure was faster and more efficient than traditional methods because it utilized the fact that for distant solar system bodies, the gravitational perturbation to the orbit is small compared to both the body’s inertial motion and the Earth’s acceleration.

The Bernstein and Khushalani code determines an error ellipse for each target in orbital parameter space and in sky position given a set of measured positions observed over several months and taken far from opposition. The power of this code is such that not only could it be used to predict future positions of our candidates, but it was anticipated that it could also be used to discriminate between potential TNOs and less distant solar system bodies.

Accordingly our observing strategy was to observe fields far from opposition, usually between 30-60°, and to plan the first recovery observations to be taken within a month of the initial observation. We took observations under these conditions for almost 2 years. At this time it became apparent that significant changes to the observing strategy were needed. The first problem was that the data reduction pipeline was still being revised and tested and as a consequence fields were typically not being processed until at least a year after their initial observations, and thus there was no possibility of recovery observations in the time-frame required for the orbit-fitting code to improve the fit of the orbit.

As a result of the observing strategy, candidates were observed on arcs typically no longer than 2 days. It was discovered that in this regime the Bernstein and Khushalani code was doubly degenerate, which biased all fits towards circular orbits. The result of this bias is shown in Figure 2.3 where a sample of 100 synthetic objects from 40 randomly selected fields were used to determine the fit predicted by the code and the difference in the fit compared to the known semi-major axis, eccentricity and inclination. In the top 3 plots, the results of all 100 objects are shown while the bottom 3 plots show the 20 synthetic bodies which had semi-major axis > 30 AU, eccentricity < 0.5 and inclination < 30° and thus have orbits similar to known TNOs. In both the upper and lower plots, the errors in the predicted and true orbital elements are significant. This can best be seen in the middle plots showing the eccentricity, where almost every object is defined to have an eccentricity 0 ± 1 and thus classifying the orbit as circular but
with an error ellipse that encompasses the entire eccentricity range. This result is the orbit-fitting codes way of indicating that it failed to find a good orbit.

Another consequence of this double degeneracy was that the Bernstein and Khushalani code was unable to discriminate between TNOs and less distant solar system bodies detected by the Survey.

A second difficulty of having this observing strategy was that by observing so far from opposition, many Jupiter-crossing asteroids were detected near their stationary points and thus commonly mistaken for TNOs. While this was a known problem from earlier work undertaken during the preliminary stages of the Survey, it was expected that follow-up observations would significantly reduce the confusion between TNOs and less distant solar system bodies.

As a result of the drawbacks of the initial observing strategy, a modified observing strategy was implemented in November, 2001. This new strategy allowed fields to be observed a maximum of 40° from opposition but gave fields within a degree of opposition the highest priority. The other major change was to allow all three observations to be taken a minimum of three hours apart. In practice a field cannot remain close to opposition for six hours, so this alteration meant
that two observations of a field were commonly taken three hours apart while the remaining observation occurred 24 hours later as before. The difference was that the sequence of observations was now flexible enough to have the 2nd and 3rd observations on a short arc if weather or other adverse conditions prevented the 2nd observation from being taken on the same night as the first observation.

2.4.5 The Observing Scheduler

To implement the observing strategy, an autonomous observing scheduler was developed. This scheduler, written in PERL, determined the best field to be observed based on more than 10 competing priorities including minimum moon distance, distance from the ecliptic and time since last observation. The scheduler is described in more detail in Appendix 2.

2.5 The Observations

Observations were taken almost continuously during the three year period from January 1st, 2000 until January 18th, 2003 when the telescope was destroyed by fire. In this time a total of 4368 fields, covering more than 2000 deg$^2$, were successfully observed three times. Of these, 1993 fields have been completely reduced as part of this thesis. The fields observed and reduced are shown in Figure 2.4 where the observed data are shown as black squares and observed and reduced fields are marked as cyan squares. Each square in this figure represents the size of a the field.

Shown in Figure 2.5 is a histogram of the time between all observations taken by the survey, where the shortest time between observations is shown in black and the longest time between observations is shown in cyan. This histogram shows that the flexible nature of the observing sequence resulted in almost 40% of fields having a pair of observations taken on the same night despite loss of observing time due to weather, etc. This plot also shows that while observations could be taken 7 days apart, the aim of taking 2 observations three hours apart and the remaining observation 24 hours later was satisfied for more than half of the fields observed.

As shown in Figure 2.6, the observing strategy was designed to concentrate the observations on the ecliptic and allow for observations up to 10° away while also biasing the observations towards southern latitudes. Of all the fields placed in the 3° wide band centered on the ecliptic, Figure 2.6 shows that more than 65% were observed. The figure also shows that significantly more fields below the ecliptic than above were observed as a result of the bias towards fields with more southern latitudes.

Another important feature of the data is the uniformity of image FWHM for the three year period of observations. As shown in Figure 2.7, the bulk of observations had a seeing of 2-3 arcseconds. This uniformity greatly simplifies the comparison between observations of the same field even if the image quality is not as good as that achieved at the world’s best sites.

The most obvious change in the observations between the initial observing
2.5. THE OBSERVATIONS

Figure 2.4: Fields observed from January 1st, 2000 to January 19th, 2003 shown as black squares. Fields which have been completely reduced are shown as cyan squares. These squares represent the size of each field. The ecliptic is shown as a red solid line.

Figure 2.5: A histogram of the performance of the observing sequence. As expected the shorter time between observations for all fields (shown in black) was always within 24 hours while the longer time lapse between observations was typically 1-2 days up to 7 days (shown in cyan).
CHAPTER 2. THE SURVEY

Figure 2.6: A histogram of the ecliptic latitudes observed by the Survey.

Figure 2.7: A histogram of the seeing for the 1993 reduced survey fields.
strategy and the final observing strategy can be seen in Figure 2.8 which is a histogram of the distance from opposition of all fields at the time of their first observation. The histogram shows three distinct peaks. The peaks at -20° and 32° are the result of the initial observing strategy which tried to maximize each observation distance from opposition while the sharp peak centered at opposition is the result of the modified observing strategy.

2.6 Data Reduction

The data reduction of the dataset was carried out by an autonomous reduction pipeline designed to quickly reduce a large amount of data with a minimum of human involvement. This pipeline, simultaneously reduced a pair of observations from a single field by fitting a World Coordinate System (WCS) to each observation, extracting all point sources down to the sky background, determin-
ing which point sources were possible moving objects and then matching point sources between the observations and searching for TNO-like characteristics.

The data reduction pipeline and the TNO search algorithm developed to extract TNO candidates from the data are detailed in Chapter 3.

2.7 Orbit fitting and Recovery Strategy

An important step in creating a well defined TNO sample is to attempt to recover all TNO candidates. Our initial recovery strategy was to reobserve all TNO candidates no later than a month after the initial observation.

However, the analysis pipeline was not completed until almost 2 years into the survey. In this situation it is important to place realistic constraints on candidate’s orbits so that time required for follow-up observations is not prohibitive.

Theoretically, three infinitely precise positions of a solar system body are enough to exactly define it’s orbit. In reality, since positions cannot be measured to that accuracy, ongoing observations are required to determine an orbit. However, observations of TNOs typically span only a few days and therefore have poorly constrained orbits.

In order to best constrain the orbits of TNOs, a number of investigators have created new techniques for orbit determination (Bernstein and Khushalani, 2000; Virtanen et al., 2003) which can be widely accessed via the web. However, the relatively short time between the first and last observations of all SEK fields made orbit determination for our TNO candidates particularly challenging. Recovery was also made more difficult as follow-up observations were typically not able to be taken until years after the initial observations. To make the best use of our survey data, Goldader and Alcock (2003) developed a technique which would not only determine the range of possible orbits for each TNO candidate but maximize the possibility of recovery while minimizing the area of sky to observe during follow-up. Their technique requires only the first and last position of each TNO candidate, the errors in these positions and the time of each observation. While we are throwing away some information about the candidate by not including the data from the second observation, the TNO search algorithm ensures that all candidates have linear motion over the course of the observations and as a result the second observation does not include much extra information.

With this input and the assumption that the orbit must be bound, a Monte Carlo simulation is performed to determine which orbits could pass through the candidates positions.

This ‘brute force’ method has been found to give comparable results to more sophisticated methods (Goldader and Alcock, 2003). An example of applying this software to a randomly selected synthetic TNO is shown in Figure 2.9 and Figure 2.10. The synthetic TNO was added to field 3004, a field a few degrees below the ecliptic which had it’s first two observations taken three hours apart on May 3rd, 2002 with the third observation taken the following night. At the time of the first observation the field was less than 2 degrees from opposition. The synthetic TNO was defined to have a semi-major axis of 46.533 AU, an eccentricity of 0.408 and an inclination of 9°. The Goldader and Alcock orbit
fitting code attempted to fit orbits with Earth-object distances between 0.1 and 100 AU with 50000 randomly selected orbits. With these input parameters the code took less than 1 minute to compute the range of possible orbits fitting the synthetic TNO.

As shown in Figure 2.9, the orbit fitting software is able to fit an appropriate range of orbits even with an arc spanning only 24 hours. As shown, both the heliocentric distance and the inclination of the object are well constrained while the range of semi-major axis and eccentricity will remain large until further observations can be taken.

The orbits fitted to the candidate can then be used to define a search region for follow-up observations. Initial tests of the software by Goldader and Alcock
showed that follow-up observations are still feasible even after several years. This was also shown to be the case for the selected synthetic TNO. A search region was determined for the synthetic TNO to test how difficult it would be to recover it 18 months after it's initial observations. This search region is shown in Figure 2.10.

Figure 2.10: A plot of the predicted position of the synthetic TNO on the 3rd of October, 2003 which is 1.5 years after initial observations of the field to which the synthetic TNO was added. The cyan region represents the predicted position from each valid orbit with eccentricity < 0.4 and the grey region represents orbits with eccentricity > 0.4. The true position, based on the synthetic TNOs known orbital elements, is represented by the black square.

Figure 2.10 shows the region which must be searched in order to recover the synthetic TNO on the 3rd of October, 2003 which is 1.5 years after the object was 'observed'. As the bulk of TNOs have orbits with eccentricity < 0.4, a typical strategy for follow-up would be to observe the grey shaded region and then, if the TNO failed to be recovered, the cyan region would then need to be observed. The widest strip of grey shaded region covers 0.5 hours in RA and 1.5 degrees in Dec and is ~ 0.5° wide. The entire region could be covered by a telescope with a 0.5 deg$^2$ field-of-view in 100 fields or about 4 hours. Thus the recovery
observations would only be at the cost of 1 night's observations.

While not the intended use of this software, the determination of orbits has become a tool by which candidates are ranked for follow-up observations. Candidates which are fitted with orbits with semi-major axis > 30 AU are ranked as probable TNO candidates and given the highest priority for follow-up. Candidates which are fitted with orbits with semi-major axis between 5 and 30 AU are ranked as possible centaur candidates and are given a medium priority for follow-up. Candidates are given the lowest priority if the fitted orbits have semi-major axis < 5 AU as these are usually asteroids close to their turn-around point masquerading as TNO-like objects. Using this strategy, time spent on follow-up observations can be scheduled to the greatest benefit.
Chapter 3

Data Reduction

"A complex system that works is invariably found to have evolved from a simple system that worked"
John Gall

3.1 Introduction

Gone are the days when, like Tombaugh, one person can search an entire night’s observations on the following day by ‘blinking’ pairs of images. The large volume of data generated by a large sky survey such as the SEK survey requires an efficient processing method with a minimum amount of human intervention. Our survey also presents several unique challenges due to fields having 3 sets of observations, in both red and blue filters, all taken under different conditions.

In this chapter I describe the processes involved in reducing the data in order to extract potential TNO candidates. Also detailed in this chapter are the tests which were conducted to understand the biases inherent to the Survey.

3.2 The Data Reduction Pipeline

The Survey’s data reduction pipeline was designed to process the three observations of each field twice, firstly by simultaneously reducing observations 1 and 2, and then reducing observations 2 and 3. Firstly, the data reduction pipeline obtains the raw output from each of the 16 amps and combines them into 8 chips (section 3.3 and section 3.4). Each chip is then fit with a World Coordinate System (section 3.5). Next, the relevant members from the synthetic population of outer solar system bodies are added to each observation (section 3.6). Then the positions and magnitudes of all objects are extracted using DoPHOT (Schechter et al., 1993) (section 3.7) and the pixel coordinates are transformed to celestial coordinates using an IRAF\textsuperscript{1} routine.

\textsuperscript{1}The Image Reduction and Analysis Facility is distributed by the National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc. (AURA), under the cooperative agreement with the NSF.
3.3 Initial Raw Reduction

During the next stage of the pipeline, positions and magnitude of all detections from each observation are compared and those not found in both observations are classified as transient detections (section 3.9). These transient detections are then matched against both known objects recorded at the MPC and the added subset from the synthetic population (section 3.10).

Once the field has undergone both passes through the data reduction pipeline, the next step is to take the transient objects found in all three observations and search for sets of three detections, which potentially correspond to the same object, and which has TNO-like characteristics. This search is undertaken using an algorithm designed to take advantage of the unique features of the Survey data (section 3.11).

Finally, to confirm that a TNO candidate is a true outer solar system object, it is confirmed as a moving object with a check by eye (section 3.13) and then fitted with a range of valid orbits (section 3.14). This then determines each candidate’s priority for follow-up observations, and the follow-up region which must be observed to ensure that the candidate is recovered.

Considerable effort was put into optimizing the pipeline such that real-time analysis was possible. Unfortunately, this point was only reached after the completion of Survey observations.

3.3 Initial Raw Reduction

After each observation is made, the raw data is read off each CCD using 2 amplifiers which create 16 amplifier images (see Figure 2.2). The images are numbered from 0-7 and then labeled with a 0 or 1 to indicate which half of the chip they correspond to, such that amplifier images 3.0 and 3.1 correspond to each half of chip 3 for example.

Each of the amplifier images are corrected by a superflat before being copied to an off-site storage facility. This superflat was created at the beginning of the survey by obtaining the median value for each pixel based on 200 observations taken in non-crowded regions and then dividing this flatfield by a super domeflat created from 200 domeflats. Over the course of the Survey it was discovered that the telescope camera system was remarkably stable with changes to the flatfield varying by less than 1% per year.

Next, a program called *Quicklook*, written by B. Schmidt, (see Section 3.5 for details) was run on a single amplifier image obtain a rough estimate of the image’s sensitivity. Observations which have a sensitivity fainter than $m_R > 19$ are considered to be of high enough quality and added to the survey database. If an observation fails the quality cut then it is recorded in the observing log but not included in the survey data. This allows the field to remain available to the Survey observation scheduler so that a replacement observation may be taken as soon as the scheduler is next queried.
3.4 Combining the Data

Once a field has had two successful observations taken, it becomes available to the automated data reduction pipeline. The first of this pipeline is to find the amplifier images for each of the two observations which are then copied to a local directory for reduction. Next, the sky brightness for each amplifier is calculated by finding the median pixel value. The two amplifier images which correspond to the same chip are then scaled by the sky brightness so that the gain (e⁻/ADU) is constant across the entire chip. Then, using several IRAF routines, the amplifier images of each chip half are joined together and the raw image is converted to a standard fits format so that each image is of the form Image_i.fits, where the red chip images correspond to i = 0-3 and the blue chip images correspond to i = 4-7.

The next step of the pipeline is to remove known defects by multiplying each of the 8 chips by a chip ‘mask’. These masks were made at the beginning of the Survey during the superflat process described above. This mask is simply an image where pixels which have significant variance from the mean are assigned a value of zero while all other pixels are given a value of one. By multiplying each chip by their mask, the known defects are effectively screened out which greatly reduces the number of such image defects being erroneously recovered as transient objects. The last step at this stage of the pipeline is to transpose each chip so that north is roughly up and east is left giving all chips the same orientation and making them easier to process through the remaining stages of the pipeline.

3.5 World Coordinate System

For each chip, SExtractor (Bertin and Arnouts, 1996) is used to quickly obtain the position and flux of all objects with a peak pixel value greater than 10 times the variance of the measured Poisson sky background. This list is sorted by brightness and then matched to the position of stars brighter than \( m_R < 16 \) in the USNO-A2.0 catalogue² (Monet et al., 1998) using a triangular matching algorithm (Germany et al., 2004) to transform the pixel position of the objects to a standard world coordinate system. The RMS fit of this transformation has a typical error of 0.25″ dominated by the positional uncertainty in the catalogue. The coordinate transformation is then recorded in the header of each chip image.

Next, QuickLook is run on each chip to determine the FWHM, ellipticity and sky brightness. The red and blue zero points are also calculated by comparing the extracted objects with the photometry given for the matched stars from the USNO-A2.0 catalogue. From photometric nights, the zero point of bright stars in the USNO-A2.0 catalogue was measured to have an RMS uncertainty of 0.2 magnitudes.

²www.nofs.navy.mil/projects/pnm/USNO02doc.html
3.6 Adding Synthetic Data

As described in the following subsections, the relevant objects from the synthetic dataset are added to the appropriate observation with the scaled PSF of a star from the observation and are then treated in the same way as for real moving objects during the remaining reduction and the human check of candidates which ensures that the survey remains double-blind.

The SLAlib (Wallace, 1994) routine, slaPlante, modified to output the RA and Dec in J2000 coordinates, determines the position of each object at midnight and 1am on the night of each observation given their known orbital elements. By comparing the two positions, an approximate velocity is obtained and both the velocity and the position of each object is output to a file.

By assuming that the objects are traveling in a straight line, the position of the object at midnight and its velocity are used to give a rough estimate of the position at the time of each observation. Objects which lie within a degree of the field then have their exact position calculated and if they are found to lie within a chip boundary, their red and blue magnitudes calculated. If both magnitudes are between 17.5 and 23, the synthetic object is selected to be added to the chip. Typically between 2-12 objects are added to each observation.

Next, a canonical PSF for the stars in the image is determined which can then be used as the model for adding the selected synthetic objects. All the stars in a chip brighter than $m_R = 17.5$ found by SExtractor (Section 3.5) and identified in the USNO-A2.0 catalogue, then have their observed magnitudes converted from raw flux using the previously measured zero point. All stars which have an observed magnitude within 0.25 magnitudes of their catalogue magnitude are then sorted by brightness. This creates a sample of bright stars relatively free of nearby stars. Typically this set is of order $\sim 100$ stars. In the case where the set contains less than 10 stars, no synthetic objects are added to the chip. Since this chip's detection efficiency cannot be measured it is removed from the survey data. Note this does not exclude the field's remaining chips from the survey data and so only has a small impact on the overall sky coverage of the Survey.

Following the method of DoPHOT for fitting the PSF (see Section 3.7), an empirically determined 7-parameter truncated power series of a Gaussian, known as a Gaussian, is fitted to each star in the list and the fit and RMS are determined. The PSFs of the top 10 best fit stars, where best fit is based on how well the star can be subtracted from the image using the calculated Gaussian, are then compared and the PSF model which best subtracts all 10 stars from the image is selected as the canonical PSF for that chip.

To add the synthetic objects, the canonical PSF is scaled to the appropriate height. using the zero point measured in Section 3.5 and inserted in the chip image at the desired location.
3.7 Extracting Point Sources

Each image is given a score which is proportional to the sky limited Signal-to-Noise Ratio (SNR) of the image as determined by Equation 3.1:

\[ \text{score} = \left< FWHM \right>^2 \times \sqrt{\left< \text{SKY} \right>} \] (3.1)

where \( \left< FWHM \right> \) and \( \left< \text{SKY} \right> \) are the average full-width at half-maximum and average sky background across the 8 chips.

The image with the lowest score and thus the best SNR, is selected to be the template image while the other image becomes the program image.

The next stage of the pipeline is to extract all point sources from each image using DoPHOT, a model-based fitting code that systematically searches for detections in two-dimensional digital array images of the sky and produces positions, magnitudes and crude classifications for each detection. A central feature of this program is its use of a distinct model for every type of point source to be identified in the image, including cosmic rays, stars, binary stars and galaxies (Schechter et al., 1993). Each model is fitted to the data using an iterative non-linear weighted least-squares scheme and the best fit then becomes the classification for that point source.

DoPHOT is designed to make successive passes over the data to identify progressively fainter detections at user specified threshold levels down to an input sky background. Once DoPHOT has recovered and classified a detection, it is subtracted from the image using the fitted model, which allows nearby point sources to be fitted with minimal contamination.

For our Survey, DoPHOT is initially run on the red image of the template observation in its standard mode with the average FWHM and the sky background of the image as input parameters. DoPHOT searches for all detections above this sky background and outputs an index for the detection, a classification according to the best fitting model and the measured pixel position, magnitude and error in magnitude as well as giving the error in the fit for each of the 7 model parameters.

During the next step, the blue template image, and both the red and blue images of the program image are run through DoPHOT in fixed position mode. In this mode the positions of the detections from the red template image become one of the input parameters along with the average FWHM and sky background of the program image. During the first stage of this ‘warmstart’ mode, DoPHOT attempts to model a point source at the position of each detection from the red template image before returning to standard mode and extracting any new detections from the image.

The final step is to convert the pixel coordinates of each detection to celestial coordinates using the IRAF routine `wctran` and the previously determined world coordinate transformation.

3.8 Transient detections

All detections extracted to this point could correspond to possible transient object candidates. Some detections however are the result of obvious chip defects, badly
extracted point sources or are transient events due to variable stars, cosmic rays etc., rather than moving objects and must be removed before the search for TNOs can begin.

3.8.1 Cosmic ray rejection

It is important to remove cosmic rays as viable point sources since their are transient events and would contaminate the set of potential TNO detections. To remove the majority of cosmic rays, those point sources extracted by DoPHOT and fitted as cosmic rays (ie given a type 8 designation) are omitted. All other detections by DoPHOT, even those which are modeled as galaxies and binary stars are included. This is to admit the possibility that some detections may have been misclassified. As galaxies and stars are stationary, most are never considered as transient objects, and those which are can be quickly ruled out during the human check of all candidates. The cosmic rays not rejected during this process are easily identified and rejected during the human check in a later stage of data reduction.

3.8.2 Detections with poor SNR

DoPHOT reflects the goodness-of-fit of the PSF of a detection in it’s magnitude error. A point source extracted with a large magnitude error implies that it has a poor SNR or that is has not been well modeled. Such a detection tends to be occur for a very faint source or an artifact resulting from a few bright pixels extracted by DoPHOT from within the noise, such as part of a bad column which hasn’t been completely masked, an extended cosmic ray or scattered light due to clouds in the observation which has increased the local sky background.

Empirically, detections with a SNR < 3 are invariably spurious artifacts or objects well below the image sensitivity. To remove exclude such detections as transient candidates, all detections extracted by DoPHOT with a magnitude error > 0.31 and thus a SNR < 3, are rejected. This cut-off is shown in Figure 3.1 as a horizontal dotted line.

3.8.3 Detections with large PSF fitting errors

As noted in the last section, the fainter a detection’s fitted magnitude, the lower the SNR and consequently the higher the magnitude errors fitted by DoPHOT. We model the relationship between the magnitude and magnitude error of a detection to be a sky limited Poisson distribution with a floor of 0.005 of the form:

\[
E_M = \frac{1}{10^{-0.4(M+M_c)}} + 0.005
\]  

(3.2)

where \(E_M\) is the magnitude error of a detection with magnitude \(M\), and \(M_c\) is a magnitude offset which adjusts this curve so that half of the measured errors lie below the curve and half above. This curve is represented by the shaded grey region shown in Figure 3.1.
Figure 3.1: Plot of magnitude vs magnitude error. Detections above the dotted line are rejected due to poor SNR. The magnitude cutoff for this image is indicated by the vertical dot-dash line which for this image occurs at a magnitude, \( m_R \approx 21 \). Point sources fainter than this cutoff are excluded while the grey shaded region is determined from \( E_M \) and is the curve at which half of the points lie above the curve and half below. All detections lying above the solid curved line, determined to be a constant offset from the curve of the grey shaded region, are above the maximum acceptable error.
3.9. SEARCH FOR TRANSIENT DETECTIONS

As shown in Figure 3.1 the detections which lie significantly above this line are DoPHOTs way of indicating a poor fit to the object, which can happen if the object is the result of pixels being flooded from nearby saturated stars, or if noise in the background has been incorrectly extracted.

Once Equation 3.2 has been used to determine the offset, $M_c$, the maximum acceptable error for a given magnitude is given by the function

$$E_{M_{\text{max}}} = \frac{1}{10^{-0.4(M + M_c + 0.3)} + 0.03}.$$ (3.3)

where 0.03 is the new floor of the Poisson distribution, empirically determined to remove the bulk of detections with relatively poor magnitude errors.

This function is shown in Figure 3.1 as a solid curved line. Detections lying above this line are rejected as having poorly fit errors for their fitted magnitude.

3.8.4 Detections below the image sensitivity

Differences in the seeing and sky background between the template and program images can result in one image being more sensitive to faint objects than the other. In this case, faint detections extracted by DoPHOT from the better quality image would have no counterparts in the other image and thus could be misidentified as moving objects. To reduce this effect, detections which are not bright enough to be extracted from both images are rejected.

The minimum sensitivity for an image is at a SNR of 5 and empirically this occurs at 1.8 magnitudes brighter than $M_c$, which is the magnitude offset calculated in Equation 3.2. This offset is known as the magnitude cutoff for that chip, which in Figure 3.1 occurs at $M = 21$.

The brightest of the magnitude cutoffs calculated for the program and template chip images becomes the global magnitude cutoff for that chip unless this magnitude is brighter than 20.5, in which case the global magnitude cutoff is set to 20.5. This minimum magnitude cut-off is designed to allow objects to be considered even when one or both images are of very poor quality. All detections in the red template and red program chip images fainter than the global magnitude cutoff are excluded.

3.9 Search for Transient Detections

A transient detection is defined to be a detection which is found in one red image and not found in the other red image. TNOs are characteristically found to reflect more red than blue light due to their dusty surface (Luu and Jewitt, 1996) and thus some TNOs could be too faint in the blue to be included as a transient detection. In order to not lose such TNOs, a detection is not required to have a counterpart in the blue to be considered transient. In most cases where an object failed to be detected in the blue, it is still clear to the human eye during the confirmation stage of candidate checking indicating that DoPHOT probably did find the object but that it failed the SNR, PSF or image sensitivity cut-off.

In order to find a transient detection, each detection in the template red image is compared to all detections in the program red image. If the difference in
magnitude between a template detection and a program detection is less than 2 magnitudes and the distance between the two positions is less than 1 arcsecond, the detections are said to be matched and the detection is classified as a non-moving object (such as a star or galaxy). Detections which have no match are classified as transient detections.

Although it is not required for a transient detection to be recovered in the blue template image, if a detection is found to be transient, the red template detection is compared to detections from the blue template image in the same manner as the red program image. If a detection from the blue template image has a magnitude within 2 magnitudes of the red detection and has a position within 1 arcsecond, then the transient detection is considered to have been recovered in both colours.

Each transient detection is recorded with its position, DoPHOT classification, magnitude and magnitude error as well as a unique identifier. This procedure is then carried out with the template and program images reversed. In this way the transient detections within each observation are determined.

3.10 Match detections to known populations

A significant number of transient detections are the result of observations of previously known minor planets or are members of the subset of the synthetic population added to the field earlier in the reduction pipeline. As it is important to discriminate between known objects and new discoveries, all detections which are associated with either population are not excluded from the TNO search algorithm process, but are labeled with the relevant information which can be accessed after the human check of each TNO candidate. As this information is only available after the data has been reduced, the survey remains double-blind.

3.10.1 Match to MPC database

Based on the current best fit orbits retrieved from the MPC's orbit database, the position of all minor planets at the time of each observation is calculated using the modified SLAlib routine slaPlante and compared with the positions of the transient detections. Those detections which lie within five arcseconds of the position of a minor planet are considered to be a match and are labeled with the minor planet's name, semi-major axis and the number of observations taken at opposition which is a measure of how well the orbit has been fit.

The generous limit of 5 arcseconds was chosen to ensure that TNOs with poorly fit orbits were still correctly matched to their detections. Each candidate extracted by the reduction pipeline is individually rechecked against the MPC objects to confirm any preliminary matches found at this stages.

3.10.2 Match to Synthetic population

To determine if any of the transient detections are recoveries from the sample of added synthetic objects, the distance between the synthetic objects and each detection is calculated. As the exact positions of these objects are known, to be
a match, a transient detection must be found within 2 arcseconds of the position of a synthetic body. These recovered synthetic objects are written to a file with the relevant DoPHOT information for the detection for later reference.

### 3.11 Apply the TNO Search Algorithm

Once the output from all 3 observations of a field have been processed and the transient detections from all three observations extracted, the next step is to then compare the detections in an attempt to find sets of 3 detections, one from each observation, which could correspond to the same object being observed each time. These sets are then analysed for their similarity to slow moving objects.

Typically \( \sim 100 \) transient detections are extracted from each image and so, with no \textit{a priori} knowledge of which transient detections are of the same body, there are \( \sim 10^6 \) possible combinations. As it takes approximately 1 minute to fit an orbit using the Goldader and Alcock orbit fitting software (2003), it is not possible to use the orbit fitting software alone as a method to search for TNO candidates.

Instead, the survey developed a TNO search algorithm to quickly reduce the number of candidates while retaining only those which had TNO-like properties which could then be run through the orbit fitting software. This search algorithm was based on three assumptions:

1. TNOs are so distant that over the course of 3 observations of a field, their intrinsic motion is zero and their apparent motion is due entirely to parallax.
2. TNOs vary by less than 1.5 magnitudes in apparent brightness.
3. The relative colours of TNOs remain constant.

Using these assumptions, the search algorithm made up of 7 selection criteria was developed to match up the transient detections found in each observation and extract those with TNO-like characteristics. Some of these criteria were chosen to quickly reduce the number of candidates while other criteria were designed as more stringent tests of TNO behaviour.

#### 3.11.1 Testing the Search Algorithm

The TNO search algorithm was designed to not only be able to successfully extract objects with TNO-like characteristics but also to be able to reject the less distant objects which make up the bulk of transient detections. In order to judge the algorithms proficiency in both areas, samples from four unique populations comprising a synthetic TNO sample, a synthetic Centaur sample, a known TNO sample and a known asteroid sample were passed through the search algorithm.

All samples came from synthetic objects and MPC objects which were found to be in all three observations of 450 randomly selected survey fields whose observations were taken at a range of distances from the ecliptic and angles from opposition. Objects were determined to be in a field by using their known orbital information and the SLALIB routine \textit{slaPlant}e to calculate the position of each
object at the time of each observation. If an object was within the 0.5 deg$^2$ area of the field then it was eligible to be in a sample. An additional 50 fields were also included as they were serendipitously found to contain known TNOs.

Once the position and magnitude of each object from the 4 sample populations is calculated at the time of each observation, this information is treated as if it had been determined by DoPHOT during the previous steps of the data reduction pipeline. In this way all 4 samples were made to be as realistic as possible and were treated in the same way by the search algorithm as the transient detections.

**The Synthetic TNO sample**

The synthetic TNO sample was defined to be all synthetic objects found to lie in all three observations of a field from the 500 selected fields, which had orbits with semi-major axis greater than 30 AU, perihelion greater than 25 AU, inclination less than 30° and maximum change in magnitude of less than 3. These values were chosen to reflect the range of orbital parameters of known TNOs and contained 1042 objects.

As shown in Figure 3.2 the objects in this sample covered a wide range in semi-major axis and eccentricity. The histogram of the inclination, shown in the topmost plot, indicates that while all inclinations up to the defined limit of 30° are sampled, more than 80% of the objects have an inclination less than 10°. This bias is a consequence of the Survey's focus on observing fields closest to the ecliptic. This population also included a wide range of eccentricities with some objects having an eccentricity > 0.75 while the population has orbits with semi-major axis between 30 and 110 AU which encompasses all three classes of known TNOs.

Also shown in Figure 3.2, the histogram of the distance from opposition of the objects in this sample ranges from 0 to 60° which is the furthest from opposition that Survey fields were observed. By covering the entire possible range of distances from opposition allows the search algorithm to be evaluated not only near opposition but also up to 60° from opposition, where confusion from less distant objects has the potential to overwhelm the number of TNO candidates needing to be checked by eye.

This sample was selected because it is a useful tool for probing the expected number of objects on orbits similar to known TNOs which would be successfully extracted by the TNO search algorithm. As the search algorithm was designed to extract objects with known TNO characteristics it is expected that a high number of these objects would be found.

**The Synthetic Centaur sample**

The synthetic Centaur sample is defined to be all synthetic objects contained in all three observations of a field from the 500 selected fields, which were not defined to be in the synthetic TNO sample, and contained 2683 objects.

As shown in Figure 3.3, this sample is named the synthetic centaur sample because it includes a large number of objects with semi-major axis between 10 and 30 AU, making their orbits very similar to known Centaurs. However, also
Figure 3.2: Histograms showing the range in inclination, eccentricity, semi-major axis and distance from opposition of the 1042 objects selected in the synthetic TNO sample.
Figure 3.3: Histograms showing the range in inclination, eccentricity, semi-major axis and distance from opposition of the 2683 objects selected in the synthetic Centaur sample.
illustrated in plots is that this sample also contains more distant objects on orbits with inclinations as high as 90° and eccentricities approaching unity. Such objects could exist but have yet to be observed as they are on highly exotic orbits which would spend little time in the regions covered by previous surveys.

This sample is useful for probing just how well the search algorithm deals with bodies outside the parameters defined for distant objects. These bodies are interesting in themselves and also because they could represent new solar system populations.

The MPC TNO sample

The MPC TNO sample was made up of minor planets recorded at the MPC, located in all three observations of a field from the 500 selected fields and defined by the MPC to be resonant, classical or scattered TNOs. This sample contained 52 known TNOs, more than 60% of which have been observed at 2 or more oppositions.

As shown in Figure 3.4, although this is the smallest of the 4 samples, the known TNOs cover a wide range of orbital parameters with inclinations up to 30°, eccentricities as high as 0.9 and semi-major axes between 38 and 94 AU. This population also samples the entire range of distances from opposition covered by the Survey which ensures that this sample is still useful for evaluating the search proficiency both near and far from opposition.

The search algorithm should be tuned to recover all known TNOs, so this sample was chosen in order to provide a strong test on how well the search algorithm met the design requirements.

The MPC asteroid sample

The MPC asteroid sample was made up of all objects recorded at the MPC, located in all three observations of a field from the 500 selected fields which were not defined by the MPC to be a type of TNO. Under this definition the sample comprised 3262 detected asteroids and 2 sets of detections of a Centaur named Hylonome.

As shown in Figure 3.5, the objects in this sample cover a different part of the parameter space to the other samples. This population is made up of objects which have inclinations up to 20° and eccentricities up to 0.4. The range of semi-major axes for the asteroids in this sample is tightly constrained to be between 2 and 4 AU as expected. The Centaur, while not visible in the histogram, has a semi-major axis of 25 AU. This sample was used to determine the success of the search algorithm in excluding these less distant and much more numerous bodies from contaminating the TNO candidates.
Figure 3.4: Histograms showing the range in inclination, eccentricity, semi-major axis and distance from opposition of the 52 objects selected in the MPC TNO sample.
Figure 3.5: Histograms showing the range in inclination, eccentricity, semi-major axis and distance from opposition of the 3262 asteroids and 2 centaurs comprising the MPC asteroid sample.
3.11.2 Magnitude Cut

All minor planet's in the solar system are bright only because they reflect the sun's light. Their brightness is given by the equation:

\[ m_R = m_{\text{sun}} - 2.5 \log_{10} \left( \frac{\rho \times d^2}{W \times R^2 (R-1)^2} \right) \]  

(3.4)

where \( m_{\text{sun}} \) is defined to be -27.1, \( \rho \) is the minor planet's albedo, \( W \) is a constant 2.25E16, \( R \) is the objects distance from the Sun and \( d \) is the diameter of the object in kilometers (Jewitt and Luu, 1995).

Based on Equation 3.4, if a constant albedo for all objects is assumed, an object’s brightness depends on it’s distance from the Sun. Thus naively a rapid method for reducing the number of possible combinations is to only consider sets of detections which are relatively close in magnitude. However many solar system bodies have been observed to periodically vary in their brightness on timescales of a few hours (Jewitt and Sheppard, 2002; Andersson and Fix, 1973; Buie and Grundy, 2000; Kristensen, 1994) which is much more rapid than would be due to changes in the Sun-object distance alone. Two processes which could explain the observed variation in magnitude are that either the object is non-spherical, and so brightness is a function of the object’s reflecting surface area, or alternatively the surface is non-uniform which causes the object to have a variable albedo. Thus the change in magnitude can be used as a discriminator between potential TNOs and both asteroids and coincidental matches, but it must be very generous so that TNOs with large variations in their brightness are not accidentally excluded. To calculate the maximum change in magnitude of a potential candidate,

\[ m_{\Delta RV} = \max_{i,j} \{ m_{R_i} - m_{R_j} \} + \max_{i,j} \{ m_{V_i} - m_{V_j} \} \]  

(3.5)

for \( i=1-3 \) and \( j=1-3 \), where \( m_R \) and \( m_V \) are the red and blue magnitudes of each detection as measured by DoPHOT. A set of three detections found in both the red and the blue image, will pass this criteria if \( m_{\Delta RV} < 3 \). For sets which have 1 or more red detections only, each \( m_{V_i} \) for \( i=1-3 \), is set to zero and the magnitude cutoff is then \( m_{\Delta RV} < 1.5 \). This cutoff is generous enough to allow for objects which may have poorly fit magnitudes, while being stringent enough to quickly eliminate a large fraction of coincidental matches and asteroids as potential TNO candidates.

Figure 3.6 shows the \( m_{\Delta RV} \) calculations for each of the 4 samples. The entire synthetic population was created such that objects can only have a maximum variance of 1.6 magnitudes in each colour over a period of six hours. Furthermore, the synthetic TNO sample is has magnitude variation less of than 3 by definition. As a result, all synthetic TNOs and 95% of synthetic Centaurs pass the criteria.

As described earlier, the bodies in the TNO and asteroid samples selected from the MPC are defined only by their orbits with no information about intrinsic magnitude variation. The change in magnitude shown in the bottom left and right panels in Figure 3.6 is the result each objects change in distance from the Sun. Since this change is small even for asteroids, all bodies in the MPC TNO and asteroid TNO samples pass this criteria.
Figure 3.6: Change in magnitude plots showing the allowed magnitude change (shaded region). All objects in the synthetic TNO sample pass this criteria (top left); all but 105 of the 2684 objects in the synthetic Centaur sample pass the criteria (top right) while every object in the MPC TNO sample (bottom left) and MPC asteroid sample (bottom right) also pass.
### 3.11.3 Direction Cut

Over the course of the Survey observations only a small fraction of a TNO's orbit is observed, a fraction so small that the motion should appear to be linear and thus a TNO should remain traveling in the same direction. Less distant objects have a much larger fraction of their orbit observed and, since this orbit is a curved path through space, the object could appear to change direction. This makes direction a quick and efficient characteristic to discriminate between TNOs and asteroids with one caveat. At any given time, some fraction of all solar system bodies appear to be at their 'turn-around' point\(^3\). As it is rare to observe a TNO at it's turn-around point, the search algorithm judges that sets of detections which result in the potential TNO candidate changing direction could either be coincidental matches or asteroids, which in both cases no longer need to be considered.

To look for changes in direction, the functions, \(G_\alpha\) and \(G_\delta\), are calculated,

\[
G_\alpha = (\alpha_3 - \alpha_2) \times (\alpha_2 - \alpha_1) \\
G_\delta = (\delta_3 - \delta_2) \times (\delta_2 - \delta_1)
\]

(3.6) 
(3.7)

Where \(\alpha_i, \delta_i\), for \(i = 1 - 3\), are the RA and Dec of the object in each observation.

\[
\Delta_D = \begin{cases} 
1 & \text{if } G_\alpha > 0 \text{ and } G_\delta > 0 \\
-1 & \text{otherwise}
\end{cases}
\]

(3.8)

If Equations 3.6 and 3.7 are positive, the set of detections results in a potential candidate which has not changed direction and the criteria is set to 1, otherwise the set of detections has failed this criteria and is assigned a value of -1 (Fig. 3.7). This criteria was chosen for speed as it typically halves the number of coincidental matches while a more stringent test of the linear motion forms one of the later selection criteria.

As shown in Figure 3.7, every member of the synthetic TNO population passes this criteria while and all of the TNOs from the MPC TNO sample were also found to have no change in their direction over the time of the 3 observations, and so passed the criteria.

Also shown in Figure 3.7, more than 99.8% of objects in the synthetic Centaur population passed the criteria and, as expected, 5% of MPC asteroids were observed at their turn-around point and were able to be excluded as possible TNO candidates.

---

\(^3\)The 'turn-around' point is the point at which the Earth, as a result of moving on a smaller orbit, appears to overtake the more distant solar system body. Observationally it appears as if the more distant solar system body slows down, comes to a stop and then changes direction.
Figure 3.7: The direction criteria is determined such that in order to pass $\Delta D$ must be positive. These plots indicate that all synthetic TNOs (top left) and MPC TNOs (bottom left) pass this criteria while 3 synthetic Centaurs failed (top right) and 169 objects from the MPC asteroid sample also failed (bottom right).
3.11.4 Change in Angular Velocity Cut

Another consequence of the assumption of linear motion for TNOs is that they should have a constant angular velocity while asteroids typically do not.

The apparent angular motion of all solar system bodies is a function of the intrinsic motion of the body and the motion of the Earth. The combination of these two vectors can produce significant changes in an object's velocity over time. However, as a TNOs intrinsic motion is assumed to be zero, its motion remains constant, which allows the difference in angular velocity to be a strong constraint on possible TNO candidates.

The difference in angular velocity, $\Delta V$, is given by the equation:

$$
\Delta V = \left| \frac{\sqrt{(\alpha_3 - \alpha_2)^2 + (\delta_3 - \delta_2)^2}}{MJD_3 - MJD_2} - \frac{\sqrt{(\alpha_2 - \alpha_1)^2 + (\delta_2 - \delta_1)^2}}{MJD_2 - MJD_1} \right| 
$$

(3.9)

Where $MJD_{1-3}$ is defined to be the modified Julian Date\(^4\) (MJD) for each observation and $\alpha$ and $\delta$ are the RA and Dec as previously discussed.

For an object to pass this criteria the angular velocity calculated between the first two observations and the angular velocity calculated between the second two observations must differ by less than 2"/hr. The choice of 2"/hr was selected to be strict enough to differentiate the true motion of asteroids and changes in velocity resulting from poorly centroided detections.

Just as for the previous selection criteria, this criteria was also chosen for speed as a more stringent test of constant motion is contained in the linear motion criteria later in the search algorithm.

Figure 3.8 shows that each of the samples had very different changes in their apparent velocity. In the top left-hand plot, all objects in a synthetic TNO sample passed the criteria and all but 7 objects in the synthetic Centaur sample also passed the criteria. An investigation of these objects found that they had either high inclinations or eccentricities. In these cases the assumption of zero intrinsic motion was not valid.

Also shown in Figure 3.8, all known TNOs showed only small changes in their velocity between the observations allowing them to easily pass the criteria. However, the bulk of the MPC asteroid sample demonstrated significant differences in their apparent angular velocity between observations, which ensured that more than half of the sample failed to pass this criteria and were able to be excluded as TNO candidates.

\(^4\)The modified Julian date is the Julian date - 245000.5
Figure 3.8: Plots illustrating the change in velocity criteria on the objects from each of the 4 samples. As shown in the top left-hand plot, the entire synthetic TNO sample lies in the allowable shaded region of the plot, while only 4 of the objects from the synthetic Centaur sample, shown in the top right-hand plot, are sufficiently close to have a significant change in their acceleration. All MPC TNOs are also shown to have little change in velocity (bottom left) while objects from the MPC asteroid sample show a significant change due to their less distant orbits resulting in 1859 objects failing this criteria.
3.11.5 Minimum Angular Velocity Cut

As a TNO's apparent angular velocity depends strongly on its distance from the Sun, for orbits with semi-major axis between 40 and 100 AU, the range of angular velocity for TNOs must be tightly constrained to be between 1.3 and 3"/hr. Note however that a TNO's distance from opposition and inclination also influence its apparent motion and if either of these is large it can significantly affect the apparent angular velocity.

To rule out sets of detections which are the result of stars with badly fit centroids, the minimum velocity is calculated.

\[ V_{\text{min}} = \min_{i,j} \left\{ \sqrt{\frac{(\alpha_i - \alpha_j)^2 + (\delta_i - \delta_j)^2}{MJD_i - MJD_j}} \right\} \]  

(3.10)

where \( \alpha, \delta \) and \( MJD \) are the RA, Dec and MJD as previously defined.

A TNO in a circular orbit would need to be beyond 120 AU to have an apparent velocity of less than 1"/hr or have been observed at 60 degrees from opposition. Since less than 10% of the fields surveyed were taken at such a large distances from opposition few objects should be wrongfully excluded at this stage which leaves the possibility of very distant TNOs being lost due to this criteria. For a TNO to be detected by the Survey it must be brighter than \( m_R \sim 21 \). Hence if a TNO had an albedo of 0.04, it would have to have a diameter more than 2500 km which is larger than Pluto, to be detected beyond 120 AU. While there is a chance that such TNOs could exist, this survey is not optimal for discovering them, so sets of detections which have an apparent motion of less than 1"/hr are excluded.

As shown in each of the plots in Figure 3.9, this criteria is not a strong discriminator between nearby and distant solar system bodies. 6% of the objects from the synthetic TNO sample were more than 80 AU from the Sun and observed at more than 30° from opposition, resulting in their apparent angular velocity being measured at less than 1"/hr while 1% of the synthetic Centaur sample also failed this criteria.

In the MPC TNO sample, all but 1 TNO passed the criteria. The TNO which failed highlights the fact that the apparent angular velocity of an object also depends on the object's inclination as discussed above. In this case, the failed TNO had an inclination of 46°. Also shown in the bottom right-hand plot of Figure 3.9, asteroids even far from opposition typically have very large apparent angular velocities so that more than 99% of the objects in the MPC asteroid sample were excluded by this criteria.

The strength of this criteria lies in it's ability to rapidly reduce the number of coincidental sets of detections which are the result of a star extracted by DoPHOT under different seeing conditions in each observation appearing to have shifted by 1" or more. Removing these potential candidates at this stage reduces the number of candidates which need to be checked by eye.
Figure 3.9: The grey shaded region shown in these plots indicates the allowable minimum velocity for a set of detections to pass this criteria. The top left-hand figure shows that all but 80 objects from the synthetic TNO sample all of which were more than 30° from opposition. 30 objects from the synthetic Centaur sample also failed this criteria (top right-hand plot). 1 object from the MPC TNO sample failed (bottom left-hand plot) while only 34 objects, all far from opposition, in the MPC asteroid sample had apparent angular velocities slow enough to fail this criteria (bottom left-hand plot).
3.11.6 Maximum Angular Velocity Cut

As discussed for the minimum angular velocity cut, TNOs should have apparent velocities between 1.3 and 3\(^\circ\)/hr if they are on circular orbits observed at opposition. This narrow range of possible values strongly marks out TNOs against less distant solar system objects which typically have apparent velocities an order of magnitude larger making the maximum velocity of an object a strong discriminator.

The maximum velocity is defined by,

\[ V_{\text{max}} = \max_{i,j} \left\{ \frac{\sqrt{(\alpha_i - \alpha_j)^2 + (\delta_i - \delta_j)^2}}{MJD_i - MJD_j} \right\} \]  

(3.11)

To allow for distant objects on highly inclined or eccentric orbits we consider sets of detections to be potential TNO candidates if their angular motion is less than 5\(^\circ\)/hr.

The maximum apparent angular velocity of an object is the strongest constraint placed on TNO candidates by the search algorithm and is typically the primary characteristic and often the only criteria used by other surveys when searching their data for TNOs.

The top left-hand plot in Figure 3.10 illustrates that all the bodies in the synthetic TNO population have angular velocities less than 5\(^\circ\)/hr. The synthetic Centaur sample, shown in the top right-hand plot cover a wide range of angular velocities. As expected, of the 15\% objects which failed the criteria, more than half had semi-major axes less than 30 AU. The known population of TNOs in the MPC TNO sample, as plotted in the bottom left-hand corner, all had velocities within the 5\(^\circ\)/hr limits apart from a single highly eccentric TNO which had an apparent angular velocity of 6.5\(^\circ\)/hr. It is likely that this object was observed near its perihelion.

The further from opposition an object is observed, the more its intrinsic motion counteracts its parallax motion. For TNOs which have no intrinsic motion there is little change to the apparent velocity, but as the MPC asteroid sample shows, the further from opposition an asteroid is observed, the slower and more TNO-like it's apparent velocity will be. This is why there is a greater risk of confusion between TNOs and less distant bodies in observations taken far from opposition. Nonetheless, the plot in the bottom right-hand of Figure 3.10 shows that all asteroids observed within 30\(^\circ\) from opposition are correctly excluded as TNO candidates, while 85\% of those asteroids observed beyond 30\(^\circ\) from opposition are also correctly excluded by this criteria which results in that 91\% of the total sample of MPC asteroids are not considered to be TNOs.
Figure 3.10: As shown in these plots by the narrow grey shaded region of acceptable values, the maximum angular velocity criteria is a strong constraint on potential TNO candidates. As shown in the top and bottom left-hand plots, all objects in the synthetic TNO sample and all but 1 object in the MPC TNO sample pass the criteria. The plots on the right-hand side illustrate the range of velocities for less distant solar system bodies. In the top right-hand plot, 399 objects from the synthetic Centaur sample have angular velocities large enough to be excluded as potential TNOs while 2964 of the 3268 objects in the MPC asteroid sample (bottom right-hand plot) fail the criteria and those that passed did so only because they were observed far from opposition.
3.11.7 Linear Motion Cut

As each candidate is observed over a period of only a few days at most, for it to be considered a TNO, its apparent motion should be constant in both time and space. This criteria is a more stringent test of both the direction and acceleration of the candidate.

To determine the motion of each set of detections, the first step is to construct a linear regression comparing time in MJD separately with RA and Dec for the three observations of each candidate. The line of best fit for each comparison is then given by the respective equations:

\[
\alpha(p_i) = \eta \times MJD_i + \alpha_0 \quad (3.12)
\]
\[
\delta(p_i) = \mu \times MJD_i + \delta_0 \quad (3.13)
\]

Once the variables \(\eta, \mu, \alpha_0\) and \(\delta_0\) have been calculated, the selection criteria is based on the average of the distance from the predicted position due to the linear fit and each observed position is given by:

\[
\Delta L = \frac{\sum_i \sqrt{(\alpha - \alpha_p)^2 + (\delta - \delta_p)^2}}{n} \quad (3.14)
\]

where \(\alpha\) and \(\delta\) are the RA and Declination.

Theoretically a TNOs observed and predicted position should be identical while asteroids, which will have a more curved path and greater acceleration during the observations, will have very different observed positions to those predicted. For a candidate to pass this criteria it must have \(\Delta L\) less than 0.25" which reflects the maximum error in the WCS fit. Faint objects which have a low signal-to-noise, could fail this criteria as a result of changes in the centroid of the PSF due to seeing differences in the observations but such objects are likely to be well below our limiting magnitude.

As shown in Figure 3.11 TNOs and non-TNOs are well separated by this criteria. All objects in the synthetic TNO population have an average change from linear motion of less than 0.25" as do all objects from the MPC TNO sample. However 1 object in the synthetic Centaur population failed the criteria while more than 83% of asteroids in the MPC asteroid sample had a change in their linear motion large enough to fail this criteria and be correctly excluded as TNO candidates.
Figure 3.11: The small size of the grey shaded region makes this criteria a strong test for TNO-like behaviour. As illustrated in both the top and bottom left-hand plots, all synthetic and MPC TNOs pass the criteria while all but 1 object from the synthetic Centaur also pass the criteria (top right-hand plot). However, as expected, 535 of the less distant objects from the MPC asteroid sample deviate from constant motion and are rejected as potential TNO candidates.
3.11.8 Maximum Ecliptic Angle Cut

A TNO with a small inclination makes the same angle to the ecliptic as does the vector defining the Earth's motion while asteroids can exhibit a wide range of angles making this criteria a potentially strong discriminator between TNOs and asteroids.

To use this TNO-like characteristic as a criteria for excluding less distant solar system bodies, the first step is to calculate the Earth's vector of motion at the time of each fields first observation, and then calculate the angle between this vector and the ecliptic which is given by the equation:

\[
\theta_{Earth} = \tan^{-1}\left(\frac{\delta}{\dot{\alpha} \cos(\delta_{E_0})}\right)
\]  

(3.15)

Where \((\dot{\alpha}, \dot{\delta})\) is the Earth's velocity vector and \(\delta_{E_0}\) is the declination of the Earth in heliocentric coordinates at the time of the first observation. To calculate the angle between a set of detections and the ecliptic, the equation is:

\[
\theta_i = \tan^{-1}\left(\frac{\delta_i - \delta_0}{(\alpha_i - \alpha_0) \cos(\delta_0)}\right)
\]  

(3.16)

As a TNOs apparent motion is assumed to be only the result of the Earth's motion, \(\theta_{Earth}\) and \(\theta_i\) should be the same. The test for this criteria is given by:

\[
\Delta \theta = |\theta_{Earth} - \theta_i|
\]  

(3.17)

For a set of detections to pass this criteria \(\Delta \theta < 10^\circ\). This criteria allows a wide range of angles to ensure that highly inclined TNOs, as well as TNOs observed further from opposition where the assumption of zero intrinsic TNO motion breaks down, are still included as potential TNO candidates. However the limit is remains strict enough that a significant fraction of less distant solar system bodies should be successfully rejected as TNO candidates by this criteria.

As shown in the two left-hand plots of Figure 3.12, both the population of synthetic TNOs and the population of MPC TNOs deviate only slightly from the angle to Ecliptic made by the Earth's motion. This results in only one TNO from the synthetic TNO sample and one TNO from the MPC TNO sample failing the criteria, both of which had their observations taken more than \(30^\circ\) from opposition and had orbits with inclinations greater than \(40^\circ\).

As discussed, less distant solar system bodies can have a wide range of angles to the Ecliptic and this is demonstrated in both plots on the right-hand side of Figure 3.12. In the case of the synthetic Centaur population, \(\sim 5\%\) of objects fail the criteria, while of the sample of MPC asteroids more than \(50\%\) have an angle to the ecliptic greater than \(10^\circ\) and are rejected as TNO candidates which makes this constraint a robust discriminator between TNOs and less distant Solar System bodies.
Figure 3.12: The range of allowed angles for a set of detections to be included as potential TNO candidates is shown by the grey shaded region. As shown in the top right-hand plot, all but one synthetic TNO pass this criteria while the criteria is also generous enough to include all but 126 synthetic Centaurs (top left-hand plot). Also, all but one MPC TNO pass the criteria (bottom left-hand plot) but, as shown in the bottom right-hand plot, less distant bodies can have a wide range of angles to the ecliptic and as a result this criteria rules out 1647 of the 3268 objects in the MPC asteroid sample.
3.11.9 Search Algorithm Proficiency

As shown in the previous subsections, each of the selection criteria employed by the search algorithm are by themselves strong discriminators between near and distant solar system bodies. To demonstrate the proficiency of employing all of the selection criteria in the search algorithm, the algorithm was first run in its entirety on the previously defined synthetic TNO, synthetic Centaur, MPC TNO and MPC asteroid samples.

As a significant fraction of the fields were observed far from opposition there was a risk that confusion from less distant solar system bodies could create an overwhelming number of TNO candidates. To determine the ability of the search algorithm to extract TNOs, near and far from opposition, all 4 samples were separated again into objects observed less than 30° from opposition and objects observed more than 30° from opposition.

<table>
<thead>
<tr>
<th>Sample</th>
<th>≤ 30°</th>
<th>&gt; 30°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synthetic TNO</td>
<td>100%</td>
<td>87%</td>
</tr>
<tr>
<td>Synthetic Centaur</td>
<td>77%</td>
<td>79%</td>
</tr>
<tr>
<td>MPC TNO</td>
<td>98%</td>
<td>98%</td>
</tr>
<tr>
<td>MPC asteroid</td>
<td>0%</td>
<td>0.01%</td>
</tr>
</tbody>
</table>

Table 3.1: Proficiency of TNO Search Algorithm based on the 4 separate samples.

As shown in Table 3.1, using all 7 selection criteria in conjunction creates a highly proficient search algorithm. This table demonstrates that within 30° of opposition, all of the objects in the synthetic TNO sample were successfully extracted. Beyond 30° from opposition the search algorithm was still able to extract more than 87% of objects from the synthetic TNO population. In order to determine if the survey is biased against finding objects with particular orbits, a comparison of the orbital elements of synthetic TNO population which passed (black dots) and failed (red filled circles) the selection criteria is shown in Figure 3.13.

In the three plots shown in Figure 3.13, the red points indicate the orbital elements of the synthetic TNOs which failed to be extracted show no strong correlation with either eccentricity or inclination. However, as shown in the bottom plot of this figure and in Table 3.1, all of the objects which failed were more than 30° from opposition and 90% of these were more than 50° from opposition. To understand this result the point at which each object failed the selection criteria must be determined. As shown earlier, the bulk of the synthetic objects which failed to pass the selection failed only the minimum velocity cut. The apparent velocity of a TNO is dependent on the fraction of the Earth’s transverse motion observed. This motion is reduced the farther from opposition the object is observed and hence, the further from opposition a TNO is observed the more likely it is to fail this criteria and not be recovered. Given this fact it may have been prudent to remove this criteria and thus increase the number of objects recovered from the synthetic TNO population. However, such change would also result in a significant increase in false TNO candidates from coincidental matches and
3.11. APPLY THE TNO SEARCH ALGORITHM

Figure 3.13: The inclination, eccentricity and distance from opposition vs semi-major axis for all objects in the synthetic TNO sample. In all three plots, the objects successfully extracted by the search algorithm are marked as black dots while the objects which failed are marked as filled red circles. The unsampled region in the eccentricity vs semi-major axis is the result of defining perihelion, \(a (1 - e) > 25\) AU, for all synthetic TNOs.
Figure 3.14: The inclination, eccentricity and distance from opposition vs semi-major axis for all objects in the MPC TNO sample. In all three plots, the objects successfully extracted by the search algorithm are marked as black dots while the two objects which failed to be extracted are marked as filled red circles.
poorly centroided stars.

As demonstrated in the plots shown in Figure 3.14, the most distinguishing feature of the two known TNOs to fail the criteria is their significantly high eccentricity. Both objects, marked in red, have orbits with eccentricity close to unity which invalidates the assumption of zero intrinsic motion for TNOs. This is why one TNO can have an angle to the Ecliptic different from the Earth's angle and why the other TNO is traveling with a higher than expected apparent velocity.

However, the strength of the selection criteria is shown best by the objects from the MPC asteroid sample. As shown in Table 3.1, within 30° of opposition, the entire sample was correctly excluded as TNO candidates, while at further distances from opposition, the TNO candidates were contaminated by only 13 objects from the MPC asteroid sample, but two of these were centaur detections and hence also good objects to extract from the data.

Table 3.1 also shows that a significant fraction of the synthetic Centaur population observed both within and beyond 30 degrees of opposition was also successfully recovered by the algorithm. Since this population consists of bodies on centaur-like orbits and possible new populations of distant solar system objects which are outside the known population of TNOs, this high fraction indicates that the survey remains sensitive to these more exotic and interesting objects.

These figures have demonstrated that for fields observed at all angles from opposition, the search algorithm is a powerful and efficient tool for selecting TNOs and rejecting less distant solar system bodies. However, the search algorithm must also have the ability to rapidly reduce the number of coincidental matches, since without this, true candidates would be swamped by spurious artifacts.

As shown in Figure 3.15, for a selected field 3562, the initial task appears daunting with more than $2 \times 10^6$ sets of 3 detections. This number is reduced at each stage of the search algorithm, less than 10 minutes of processing time, until only 15 candidates require a human check. Of these 15, 13 are rejected as spurious or asteroid candidates with 2 real TNO candidates remaining. For this particular field one of the TNOs was an object added from the synthetic sample with the other is the recovered TNO, 2002 JR146.

Figure 3.15: Flow-chart showing the total number of candidates at each stage of the TNO search algorithm for field 3562.
As a result of these tests, we conclude that the unique search algorithm developed for the SEK survey is an efficient and powerful tool for extracting the handful of possible TNO candidates from the large numbers of moving object detections.

3.12 Create Image Mosaics

Each set of detections passing the search algorithm are now classified as potential TNO candidates. At this stage each candidate needs to be individually inspected to confirm that it is a real object. Traditionally this would be done by blinking two observations of the same field to confirm that the object is detected in one observation and missing in the other. However as blinking is a time-consuming and inefficient process, mosaics of each detection in the red and blue image of an observation are created along with the same area of sky from another observation for reference. By inspecting such a mosaic, it is instantly obvious if the object is a true TNO candidate.

A mosaic is created for each of the 3 detections of a potential TNO candidate. This mosaic is made up of $4 \times 50$ pixel wide sub-images created using the IRAF imcopy routine. Two of the sub-images are centered at the position on the red and blue image of the observation where the TNO was detected, while the other two observations are centered at the same position but from the red and blue images from another observation. For example, if the mosaic was being created for the potential TNO when it was detected in the first observation, then the second observation would be used as a reference image. In essence this is the same area which would be checked if the images were blinked but without having to blink them.

The 4 images are then combined into a 1x4 mosaic where the format is red detection, red reference, blue detection, blue reference. This is shown in Figure 3.16. The Mosaic creation procedure is done for all 3 detections for each of the potential TNO candidates.

![Figure 3.16: Format of moving object candidate mosaics](image)

Once the image creation procedure is completed, each TNO candidate is made up of three mosaic images. To confirm that a mosaic shows a moving object, an object must appear in the centre of both the red and blue detection images and be missing from the centre of the red and blue reference images. This is regardless of whether the object was successfully detected by DoPHOT in the blue image.
3.13 Check fields by Eye

With such a large amount of data it is important to analyse the fields which have the highest chance of containing new discoveries as well as those fields which have the best quality observations. Accordingly, fields which had been processed to this point were given a rating based on several characteristics in order to determine the highest priority fields to be inspected by eye.

Each field was rated according to the number of TNO candidates, such that the more candidates a field had, the lower its priority. At first this may seem counterintuitive but upon studying the processed fields, it was found that the more TNO candidates found, the more likely that all the objects were made up of spurious detections. In some cases these field’s contained upwards of 100 TNO candidates and were labeled as ‘pathological’. Another advantage of biasing the ranking of fields towards low numbers of TNO candidates was that these fields could be checked quickly, increasing the total number of fields to be fully reduced.

The ranking also prioritized those fields which had been observed in good seeing conditions, which where those fields with a low FWHM, and those which had been successfully fit with a zero-point in each chip.

Finally the fields were slightly biased against fields in the northern latitudes as there was a greater likelihood that these fields would be observed by other surveys while much of the southern latitudes were uniquely available to our Survey.

As new fields became available, the ranking was redone so that the most desirable fields were always checked first.

3.14 Final Candidate Classification

The final step in the analysis pipeline is to classify each of the TNO candidates as either high or low priority for follow-up. As shown in Table 3.1 in Subsection 3.11.9, a small fraction of less distant solar system bodies can appear to have TNO-like behaviour which allow them to be selected as potential TNO candidates by the search algorithm. Such bodies must be removed so that a true measure of the number of TNOs found by the survey can be made.

Using the code developed by Goldader (2003) and described in Section 2.7, the first and last observed position of each candidate is tested with 50000 randomly selected orbits, generated such that their semi-major axes lay between 0.1 and 100 AU, while all other orbital parameters were uniformly sampled over their entire sample space with the only provision being that the orbit must be bound.

Under the assumption that all objects are correctly passed during the human check, the ability of the orbit fitting software to accurately discriminate between TNOs and less distant bodies was tested by fitting the objects which passed the search algorithm from the previously defined synthetic TNO, synthetic Centaur, MPC TNO and MPC asteroid samples. These results are shown in Table 3.2 where TNO orbits are defined to be those with semi-major axis > 30AU and eccentricity < 0.4.

As shown in Table 3.2, all but 1% of objects observed within 30° from both the synthetic TNO and Centaur sample, are correctly identified as being fitted
CHAPTER 3. DATA REDUCTION

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number with TNO-like orbits ≤ 30° from opp</th>
<th>Number with TNO-like orbits &gt; 30° from opp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synthetic TNO sample</td>
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<td>99.8%</td>
</tr>
<tr>
<td>Synthetic Centaur sample</td>
<td>99%</td>
<td>38%</td>
</tr>
<tr>
<td>MPC TNO sample</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>MPC asteroid sample</td>
<td>0%</td>
<td>38%</td>
</tr>
</tbody>
</table>

Table 3.2: Proficiency of TNO Search Algorithm on the 4 separate samples.

by TNO-like orbits. In the case of the synthetic Centaur sample, while many of these objects are not TNOs, they are distant solar system bodies and therefore important objects to recover. Also shown in the table, 100% of known TNOs from the MPC TNO sample and significantly 0% of objects from the MPC asteroid sample are fitted by TNO-like orbits for objects less than 30° from opposition, indicating that the confusion from less distant objects is likely to be insignificant for observations taken close to opposition.

In the case of objects observed more than 30° from opposition, the orbit fitting software is still able to correctly identify more than 99% of the synthetic TNOs and again 100% of the population of MPC TNOs. Also 38% of objects in the synthetic Centaur sample are identified with TNO-like orbits. Also shown in Table 3.2, 5 known objects from the MPC asteroid sample are incorrectly matched with TNO-like orbits however 2 of these objects are known centaurs and so desirable to follow-up which results in only 3 out of the 2455 objects from the MPC asteroid sample were matched with TNO-like while only 9 of the 1024 objects in the synthetic TNO and known MPC TNO populations failed in their attempt to be matched with TNO-like orbits.

From these results it is clear that the orbit fitting algorithm developed by Goldader and Alcock is a powerful tool for discriminating between TNOs and less distant objects, regardless of the short time over which the observations are taken and their distance from opposition.

<table>
<thead>
<tr>
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<th>Classification</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
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<td>$a &gt; 30$AU &amp; $e &lt; 0.4$</td>
<td>TNO</td>
<td>high</td>
</tr>
<tr>
<td>$a &gt; 10$AU</td>
<td>Centaur or unusual TNO</td>
<td>medium</td>
</tr>
<tr>
<td>$a &lt; 10$AU</td>
<td>asteroid</td>
<td>low</td>
</tr>
</tbody>
</table>

Table 3.3: The three distinct classes each potential TNO candidate is sorted into according to the types of orbits fitted by the Goldader software. Candidates which are fit by at least 1 TNO orbit are assigned a high priority for follow-up while those candidates which are only fit by asteroid-like orbits have a low probability for being TNOs are are assigned a low priority for follow-up.

As shown in Table 3.3 the priority for follow-up of the candidates was separated into three groups based on the range of orbits found by the orbit fitting software. In order to optimize follow-up for true potential TNOs, candidates which were fit by orbits with semi-major axes greater than 30 AU and eccentricity less than 0.4 were considered to be TNO-like and classified as high-priority.
Candidates which were fit by any orbit with a semi-major axis greater than 10 AU are classified as possible centaurs or unusual TNOs and were given a medium priority while also shown in Table 3.3, candidates fit only by orbits with semi-major axes less than 10 AU were classified as probable asteroids and given a low priority for follow-up observations.

3.15 Determine the Follow-up Region

Once the TNO candidates have been prioritized the next step is to propagate the valid orbits determined by the orbit fitting software to a time when recovery observations can be taken. The propagation of these orbits results in a follow-up region whose size roughly depends on the time since the candidate was discovered. For the SEK survey, recovery observations were not possible until several years after the observations were taken, which would typically require a large follow-up region to guarantee that the candidate was recovered. However, the Goldader and Alcock code was designed to constrain the position of a candidate so as to maximise the possibility of recovery while minimizing the area of sky needing to be observed to recover the object.

To test the efficiency of the orbit fitting software to create a follow-up region which would result in the recovery of a TNO even several years after the initial observations, a sample of 100 synthetic TNOs was selected from the sample of 2683 synthetic TNOs used to test the search algorithm earlier, and a follow-up region was determined for potential recovery observations taken at midnight on June 1, 2005.

As illustrated in the plots shown in Figure 3.17, the 100 synthetic TNOs have inclinations up to 30° and eccentricities as high as 0.7. The objects comprising this sample also have orbits with semi-major axes ranging between 30 and 110 AU. The bottom plot shown in Figure 3.17 is a histogram of the distance from opposition of the 100 objects which is also shown to be well sampled.

The first step is to predict the range of valid orbits as described in Section 2.7 as well as the previous section. For the selected 100 synthetic TNOs, the position at the time of the first and last observation of the field it was found in is calculated using the modified SLALIB routine slaplante. These positions along with a date and a positional error of 0.33, chosen to encompass both the error in the WCS fit and positional error of DoPHOT when centroiding the models, then became the input parameters just as in the previous section with the range of initial Earth-object distance set to be between 30 and 100 AU. The range of initial Earth-object distance is set to only consider distant solar system bodies so that only these orbits will be propagated to June 1, 2005 to form the follow-up region. This region is then compared to the true position of the synthetic TNO based on it’s ephemeris again calculated using slaplante and the defined orbital elements. The synthetic TNO is determined to be recovered if the calculated position of the TNO was within the cyan ($e < 0.4$) or grey ($e > 0.4$) region created by propagating the orbits found by the orbit fitting software.

As illustrated in the plots shown in Figure 3.18, all but 8 of the synthetic TNOs were found within the follow-up region predicted by the orbit fitting software.
CHAPTER 3. DATA REDUCTION

Figure 3.17: Histograms of the inclination, eccentricity, semi-major axis and distance from opposition of all 100 objects in the sample.
Figure 3.18: The inclination, eccentricity and distance from opposition vs semi-major axis for all objects in the MPC TNO sample. In all three plots, the objects successfully extracted by the search algorithm are marked as black dots while the two objects which failed to be extracted are marked as filled red circles.
Figure 3.19: A region 0.8 hours wide in RA and 0.5 degrees wide in Dec centered on the predicted position of each synthetic TNO at midnight on June 1, 2005 (black square). The cyan points are the positions predicted by the orbit fitting software if the orbit has an eccentricity < 0.4 while the grey points are the positions predicted from orbits with eccentricity > 0.4.
These plots show that there is no strong correlation between failing to be within the follow-up region and inclination, eccentricity or opposition.

If we analyze each of the 8 failed objects individually, each plotted in Figure 3.19, we see that objects tended to fail because they suffered from a combination of problems. Upon investigation it was found that four of the objects, shown in plots D, E, F and G, which failed to be within the predicted region were more than 100 AU from the Earth at the time their positions were calculated, putting them outside the range of parameters considered by the orbit fitting software. In all four cases if the initial Earth-object distance was extended from 100 AU to 140 AU, the follow-up region grew sufficiently to encompass the position of the TNO.

In the case of the remaining 4 TNOs which failed to be within their predicted follow-up region, candidate A was observed more than 30° from opposition, had an eccentricity of 0.401 and an inclination of 20° making it both highly eccentric and inclined. Despite these drawbacks the object was only just outside the predicted follow-up region. Candidates B and C were found to have been more than 30° from opposition when observed and were also highly inclined, which caused them to narrowly miss their predicted follow-up region. Lastly candidate H was found to be close to perihelion at the time it was observed and so accurately predicting it's orbit would have been difficult, and yet this candidate was so close to the follow-up region that it could possibly have been found in the recovery observations, depending on the size of the field-of-view of the telescope used to take the follow-up observations.
Chapter 4

Results

"If the result confirms the hypothesis, then you’ve made a measurement. If the result is contrary to the hypothesis, then you’ve made a discovery.”

Enrico Fermi

4.1 Introduction

Preliminary reduction and testing of the data was ongoing throughout the Survey and by the end of 2002 this resulted in all observed fields having been passed through the analysis pipeline and approximately one-third of all TNO candidates checked by eye. However the fires of January 2003 which destroyed the Great Melbourne telescope also destroyed the computers storing the reduced Survey data. As a result the data had to be reduced again. This second reduction was carried out with the computing facilities generously provided by the University of Pennsylvania. Using these computers 1993 fields were successfully reduced by December 2003.

From these 1993 fields, approximately 10000 candidates were extracted by the data reduction pipeline, 13 of which were confirmed as moving objects. Of these 13 objects, 3 are serendipitous recoveries of known TNOs, 2 appear to be coincidental matches of non-related moving objects, 2 are most likely asteroids and 3 candidates are potentially newly discovered TNOs.

In this chapter I describe the circumstances under which each candidate was detected and the classification of each object as determined from the Goldader and Alcock (2003) orbit fitting software described in previous chapters.

Images and further data for each candidate can be found in Appendix B.

4.2 Candidate 1

Candidate 1 was first observed on May 25th, 2000 while the final two observations were taken ~7 hours apart on May 31st, 2000. This candidate was observed at $27^\circ$ from opposition and $1^\circ$ south of the ecliptic. It appeared point-like and separate from all nearby stars and was extracted with a magnitude $m_R \sim 18.8$ making it the brightest candidate found by the Survey.
Figure 4.1: The orbital elements of Candidate 1 as predicted by the orbit fitting software. A histogram of the Earth-object distance which shows valid Earth-object distances < 3AU and 40-60 AU (Plot A) while the predicted inclination distribution has a peak at ~ 2° (Plot B). The plot of semi-major axis vs eccentricity (Plot C) suggests that, for eccentricity < 0.4, the semi-major axis is either < 5 AU or between 38 and 68 AU.
As the plots in Figure 4.1 indicate, the 6 day arc this candidate was observed on was enough for the orbit fitting software to constrain the valid orbits. From the histogram of the Earth-object distance (Plot A), the candidate was either within 5 AU of the Earth or between 40 and 60 AU from the Earth. According to the inclination histogram (Plot B), the predicted inclination of candidate 1 is $\sim 2^\circ$. The semi-major axis vs eccentricity plot (Plot C) confirms that valid orbits for Candidate 1, assuming eccentricity < 0.4, have either semi-major axes < 5 AU or between 38 and 68 AU. As a result of these plots this candidate most likely has a low inclination and is either an asteroid or TNO.

Asteroids should typically appear to be extended in observations. As the observations of this candidate were all round and point-like, it is unlikely that this object is an asteroid, however follow-up observations are required to discriminate between the two possibilities. Since the candidate was fitted by orbits with semi-major axis > 30 AU and eccentricity < 0.4 it was classified as a TNO and was given a high priority for follow-up.

### 4.2.1 Follow-up of Candidate 1

Follow-up observations were originally planned to be taken with the Great Melbourne Telescope so that the same data reduction could be carried out on the new observations. However, since candidates were not selected until well after the telescope had been destroyed, the follow-up observations were instead, carried out on the 40 inch telescope at Siding Spring Observatory. Candidate 1 was allocated time for follow-up observations in February, 2004. The region to be search was defined by the predicted positions for the candidate based on the valid orbits previously determined. This search region is shown in Figure 4.2.

Figure 4.2 shows the region of sky where the candidate is predicted to be found in February 2004 predicted by the orbit fitting software, assuming the candidate is a TNO. As original observations of the candidate were taken almost 3 years ago, the search area is quite large, spanning an hour in RA and 4 degrees in Dec as shown in Figure 4.2. This plot is colour-coded into two regions, those points which are grey are the predicted positions for valid orbits which have eccentricity > 0.4 while the cyan points denote the predicted positions for the candidate from orbits with eccentricity < 0.4. If the candidate is similar to known TNOs then the highest probability is for it to be recovered in the cyan region. As a result initial follow-up for candidate 1 covered the cyan region as shown in Figure 4.3 which is an enlarged view of the cyan search region shown in Figure 4.2. Overlaid on this region are fields denoting the 40 inches field-of-view. Due to the narrow width of the predicted search area, only 4 fields are required to observe the entire cyan region. Follow-up observations consisted of two 300 second exposures per
4.2. CANDIDATE 1

Figure 4.2: Region for Candidate 1 follow-up in February 2004. The predicted positions of the candidate for TNO-like orbits with eccentricity > 0.4 (grey points) and with eccentricity < 0.4 (cyan points).

Figure 4.3: An enlarged view of the cyan region shown in Figure 4.2 overlaid with the fields observed during the follow-up of this candidate.
field. As a result it took only 40 minutes of dedicated observing to complete all of the follow-up observations.

The 40 inch was sufficiently different from the Great Melbourne telescope that the recovery observations could not be processed by the same way as the initial observations, by the analysis pipeline. Instead a similar algorithm was used to search the follow-up observations. After careful scrutiny of all follow-up observations, no TNO-like moving object was recovered.

As a result of searching these first follow-up observations, candidate 1 is unlikely to be a typical TNO. However, the possibility that this candidate is a high eccentricity TNO cannot be ruled out until follow-up observations of the grey survey region are conducted.

4.3 Candidate 2

This candidate was first observed on May 25th, 2000 with the final two observations taken on June 6th, 2000. Candidate 2 was observed at 18° from opposition and 1.3° degrees above the Ecliptic. With a magnitude \( m_R \sim 20.4 \), the candidate was at the edge of the magnitude limit and so while it was successfully detected in each of the 3 red images, it was only detected in the blue image of the first observation. However a visual check confirmed a point-like moving object in both the red and blue images from all three observations.

<table>
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<td>-15:20:33.3</td>
</tr>
</tbody>
</table>

Table 4.2: Details of Candidate 2

This candidate was observed over an 11 day arc which resulted in the range of valid orbits found by the orbit fitting software was significantly constrained. The orbital elements of these valid orbits are shown in Figure 4.4. According to the histogram of the Earth-obj distance (Plot A), candidate 2 could either be within a few AU of the Earth, or between 30 and 50 AU from the Earth. The inclination distribution (Plot B) shows two distinct possibilities, the peak at \( \sim 2^\circ \) due to the the valid asteroid-like orbits while the peak at \( \sim 19 \) comes from the valid TNO-like orbits. The two distinct classes are also shown in the semi-major axis vs eccentricity plot (Plot C). In this plot, assuming eccentricity < 0.4, this candidate is predicted to have either a semi-major axis < 5 AU or between 23 and 58 AU.

As in the case for candidate 1, this candidate is unlikely to be an asteroid as it has the expected stellar profile in all three observations. To confirm that this object is in the EKB, follow-up observations are required. As candidate 2 has valid orbits with semi-major axes > 30 AU and eccentricity < 0.4 it is classified as a TNO and given a high priority for follow-up. Further, the range of semi-major axis, eccentricity and high inclination predicted by the orbit fitting software suggest that this candidate is potentially a new resonant TNO.
Figure 4.4: The valid orbital parameters predicted by the orbit fitting software. A histogram of the valid Earth-object distance (Plot A) suggests that this object is either less than 5 AU or between 30-50 AU from the Earth. The inclination distribution has a peak at $\sim 2^\circ$ and at $19^\circ$ (Plot B) while the semi-major axis vs eccentricity plot (Plot C) shows that both asteroid-like and TNO-like orbits are valid for this candidate.
4.4 Candidate 3

Candidate 3 was observed between the 25th and 31st of April, 2001. Observations were taken almost $60^\circ$ from opposition and $1.86^\circ$ below the ecliptic. This candidate was successfully detected at a magnitude $m_R \sim 19.7$, in both the red and blue images of all three observations. This candidate was also successfully matched to the predicted positions of known TNO 1999 $DE_9$.

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</tbody>
</table>

Table 4.3: Details of Candidate 3

Figure 4.5: The predicted orbital parameters as fitted by the orbit fitting software for the recovered TNO, 1999 $DE_9$. The known orbital parameters of 1999 $DE_9$ are shown as a black square (offset on the y-axis for clarity in Plot A and C). In the histogram of Earth object distances (Plot A) the range of valid orbits encompass the known value of the TNO. The is also true for the inclination histogram (Plot B) and the semi-major axis vs eccentricity plot (Plot C).
4.5. CANDIDATE 4

Figure 4.5 illustrates the power and flexibility of the orbit fitting software. 1999 \( DE_9 \) is a scattered TNO with an eccentricity of 0.425, semi-major axis of 56.15 AU and an inclination of 7.6°. It was 33 AU from the Earth during these observations, which were taken on a 4 day arc and at great distance from opposition. In this situation typically it would be difficult to constrain the orbital elements. However the orbit fitting software is able to successfully predict an inclination of \( \sim 8° \) while the true eccentricity and semi-major axis were also encompassed by the range of valid orbital elements. As this candidate was fit by orbits with semi-major axis > 30 AU and eccentricity < 0.4, 1999 \( DE_9 \) was correctly identified as a TNO and given a high priority for follow-up.

4.5 Candidate 4

All three observations of candidate 4 were taken on the 17th and 18th of May 2001 when the field was 55.6° from opposition and 2° south of the ecliptic. This candidate was detected at a magnitude \( m_R \sim 18.1 \), which ensured that it was easily recovered in both the red and blue images of all three observations.

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</tbody>
</table>

Table 4.4: Details of Candidate 4

Even though this candidate was only observed on a 1 day arc at a time when it was far from opposition, the orbit fitting software was still able to place constraints on the orbit. As shown in Figure 4.6, the object’s initial Earth-object distance (Plot A) could fall anywhere between 1 and 45 AU while its inclination is predicted to be \( \sim 4° \) (Plot B). If the eccentricity < 0.4, then the semi-major axis vs eccentricity plot (Plot C) indicates that the object could be an asteroid with a semi-major axis \( \sim 3 \) AU or a centaur with a semi-major axis between 20 and 30 AU. Follow-up observations will rule out one of these possibilities and as this object has valid orbits with semi-major axis > 5 AU and eccentricity < 0.4, this candidate is classified as a potential centaur and given a medium priority for follow-up.
Figure 4.6: The valid orbits fitted to candidate 4 by the orbit fitting software. The histogram of Earth-object distance (Plot A) suggests that this candidate has an Earth-obj distance < 45 AU. The inclination histogram (Plot B) has a peak at ~ 4°. While the semi-major axis vs eccentricity plot (Plot C) shows both asteroid-like and TNO-like orbits are valid for this candidate.
4.6 Candidate 5

This candidate was observed on the 17th and 18th of May, 2001, directly after the observations of candidate 4, when it was 60° from opposition and 3° south of the ecliptic. In all three observations the candidate was detected with a magnitude of $m_R \sim 19.5$ and was distinct and point-like in each red and blue image.

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Table 4.5: Details of Candidate 5

Figure 4.7: The range of valid orbital elements fitted to candidate 5 by the orbit fitting software. As shown in the histogram of the Earth-object distance (Plot A), this candidate was within 28 AU of the Earth while the inclination histogram (Plot B) has a peak at $\sim 4°$. The semi-major axis vs eccentricity (Plot C) has valid orbits with semi-major axis up to 10 AU for eccentricity $< 0.4$. 
Candidate 5 was observed far from opposition and on a short arc making its orbit difficult to constrain. According to the Earth-object histogram (Plot A) of Figure 4.7, this distance is only constrained to be < 28 AU. However, the orbit fitting software is able to predict an inclination of 5° (Plot B) and semi-major axis < 10 AU for eccentricity < 0.4 (Plot C) for this candidate. Thus, the most likely scenario is that this object has a low eccentricity and inclination and is orbiting between 5 and 10 AU. It may also be that this object is an asteroid at turn-around and so follow-up observations are required to discriminate between the two possibilities.

As only a handful of orbits with semi-major axis > 10 AU for eccentricity < 0.4 were valid for this candidate, it was classified as an asteroid and given a low priority for follow-up.

4.7 Candidate 6

This candidate’s observations were taken on May 21st and 23rd, 2001. These observations were taken 58° from opposition and 0.6° north of the ecliptic. Good seeing during all three observations ensured that this \( m_R \sim 19.9 \) object was clearly visible in both the red and blue images of all three observations.

\[
\begin{array}{|c|c|c|c|c|c|}
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\text{MJD} & \text{Seeing} & \text{\( m_R \)} & \text{\( m_V \)} & \text{RA} & \text{Dec} \\
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\hline
\end{array}
\]

Table 4.6: Details of Candidate 6

The three plots in Figure 4.8 indicate that this candidate is most likely an asteroid. As a result of the candidates short arc and distance from opposition, it’s apparent motion is slow enough that is has been mistaken for a more distant object by the TNO search algorithm. However, the orbit fitting software has almost completely ruled this possibility out unless the candidate is on a very exotic orbit. As shown in the plots in Figure 4.8, the candidate is predicted to have an Earth object distance < 8AU (Plot A), an inclination < 2° (Plot B) and semi-major axis < 4 AU for eccentricity < 0.4.

As the object is not fit by any orbits with semi-major axis > 10 AU for eccentricity < 0.4, this candidate is classified as an asteroid and given a low priority for follow-up.
Figure 4.8: The range of fitted orbital parameters for candidate 6. According to the Earth-object histogram (Plot A) this object was within a few AU while the inclination distribution (Plot B) suggests that this object is on a circular orbit. The semi-major axis vs eccentricity plot (Plot C) shows that the only valid outer solar system orbits occur for eccentricity > 0.85.
4.8 Candidate 7

Candidate 7 was observed on the 23rd and 24th of May 2001. This candidate was observed at 58° degrees from opposition and 2° north of the ecliptic. This candidate was detected at a magnitude of 19.9 and appeared not to fit a stellar profile in both the red and blue images of the first observation suggesting that this candidate was an inner solar system body.

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Table 4.7: Details of Candidate 7

Figure 4.9: The range of orbital elements fitted to candidate 7 by the orbit fitting software. The Earth-object histogram (Plot A) indicates that the object was at most 32 AU from the Earth at the time of the observations. The semi-major axis vs eccentricity plot (Plot C) shows that for eccentricity < 0.4, the semi-major axis of this candidate is < 10 AU while the peak of the inclination distribution (Plot B), the occurs at ~2°.
According to the plots shown in Figure 4.9, as a result of this object being observed on a 1 day arc at 60° from opposition, a large range of orbits were fit by the orbit fitting software such that the range of Earth-object distances (Plot A) placed this candidate anywhere within 32 AU from the Earth during the observations. However, the arc was long enough to predict an inclination of \( \sim 2^\circ \) (Plot B) and rule out outer solar system orbits with eccentricity < 0.75 (Plot C).

As this candidate had no valid orbits with semi-major axis > 10 AU for eccentricity < 0.4, it was classified as a probable asteroid and given a low priority for follow-up.

### 4.9 Candidate 8

Observations of this candidate were taken on May 25th and May 27th, 2001 at 59° from opposition and 3° south of the ecliptic. Although this object had a shape which was consistent with the stellar PSF of the image and was detected with an apparent magnitude \( m_R \sim 19.2 \), upon visual inspection it was found to be slightly blurred in both the red and blue images of the third observation as a result of the poor seeing.

<table>
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<tr>
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<th>Seeing</th>
<th>( m_R )</th>
<th>( m_V )</th>
<th>RA</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>52054.66720</td>
<td>2.09</td>
<td>19.23</td>
<td>20.25</td>
<td>20:09:27.50</td>
<td>-23:06:48.0</td>
</tr>
<tr>
<td>52056.61846</td>
<td>3.09</td>
<td>19.03</td>
<td>20.14</td>
<td>20:09:20.93</td>
<td>-23:07:03.8</td>
</tr>
</tbody>
</table>

Table 4.8: Details of Candidate 8

According to the plots in Figure 4.10 two distinct classes of orbits fit the data. As shown in the Earth-object histogram (Plot A), either this object was less than 10 AU from the Earth at the time it was observed, or between 20 and 60 AU. The inclination distribution (Plot B) shows a peak at \( \sim 6^\circ \) which corresponds to those orbits within 10 AU of the Earth and a peak at \( \sim 14^\circ \) due to the more distant orbits. These two classes are also apparent in semi-major axis vs eccentricity plot (Plot C). In this plot, for eccentricities < 0.4, either this object is an asteroid with a semi-major axis < 5 AU or it is a TNO with a semi-major axis between 20 and 40 AU. If the candidate is in the outer solar system, its high inclination and the Neptune-like semi-major axis suggest that it is potentially a resonant TNO.

As this candidate has valid orbits with semi-major axis > 30 AU and eccentricity < 0.4, it is classified as a potential TNO and a high priority for follow-up.
Figure 4.10: Results for candidate 8 from the orbit fitting software. From the Earth-object histogram (Plot A), this object was either < 10 AU or between 20 and 60 AU from the Earth. The inclination distribution (Plot B) shows peaks at \( \sim 6^\circ \) and \( \sim 14^\circ \). The semi-major axis vs eccentricity shows that for eccentricities < 0.4, either the semi-major axis is < 5 AU or between 20 and 42 AU.
4.10 Candidate 9

Candidate 9 was observed on June 14th and 15th, 2001 at 55° from opposition and 1° north of the ecliptic. This candidate was detected and had a stellar profile in each of the red and blue images of all three observations, however in observations 1 and 2, the detected images are slightly blurred due to poor seeing.

<table>
<thead>
<tr>
<th>MJD</th>
<th>Seeing</th>
<th>$m_R$</th>
<th>$m_V$</th>
<th>RA</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>52074.71635</td>
<td>3.48</td>
<td>19.27</td>
<td>20.01</td>
<td>21:13:59.33</td>
<td>-14:57:46.9</td>
</tr>
</tbody>
</table>

Table 4.9: Details of Candidate 9

Figure 4.11: The range of valid orbital elements found by the orbit fitting software. The histogram of the Earth-object distance (Plot A) predicts that the object was within 30 AU of the Earth during the observations. The inclination distribution (Plot B) has a peak at $\sim 2^\circ$ and the semi-major axis vs eccentricity plot (Plot C) shows that for eccentricity $< 0.4$ the semi-major axis is $< 12$ AU.
Figure 4.11 illustrates that while this candidate was observed on a 1 day arc and at a great distance from opposition where asteroids can be confused for TNOs, the orbit fitting software has ruled out this object as a potential TNO. According to the Earth-object distance (Plot A), this candidate was a maximum of 30 AU from the Earth during the observations. The inclination distribution (Plot B) shows that the most likely inclination for this object is \( \sim 2^\circ \) while the semi-major axis vs eccentricity plot (Plot C), for an eccentricity < 0.4, the semi-major axis is either less than 5 AU or between 10 and 12 AU.

While, both asteroid and centaur type orbits fit this candidate, as this candidate has valid orbits with semi-major axis > 10 AU for eccentricity < 0.4, it is classified as a potential centaur and given a medium priority for follow-up.

4.11 Candidate 10

Observations of this candidate were taken on April 12th and 18th, 2002 at 13° from opposition and \( \sim 6^\circ \) south of the ecliptic. This object was detected with a magnitude \( m_R \sim 20.5 \) putting it at the threshold of detection but good seeing ensured the object was clearly visible and with a good stellar PSF in all three observations. The positions of this candidate were matched to the positions of 2002 \( JR_{146} \), a scattered TNO.

<table>
<thead>
<tr>
<th>MJD</th>
<th>Seeing</th>
<th>( m_R )</th>
<th>( m_V )</th>
<th>RA</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>52376.72223</td>
<td>1.55</td>
<td>20.46</td>
<td>21.24</td>
<td>14:15:42.70</td>
<td>-19:50:10.1</td>
</tr>
<tr>
<td>52382.58715</td>
<td>2.10</td>
<td>20.53</td>
<td>21.20</td>
<td>14:15:09.84</td>
<td>-19:47:13.0</td>
</tr>
<tr>
<td>52382.73392</td>
<td>2.33</td>
<td>20.59</td>
<td>21.30</td>
<td>14:15:09.00</td>
<td>-19:47:08.3</td>
</tr>
</tbody>
</table>

Table 4.10: Details of Candidate 10

As observations were taken close to opposition over a 6 day arc, the orbit-fitting software was able to successfully predict the orbit of 2002 \( JR_{146} \). As shown in Plot A of Figure 4.12, the Earth-object distance of 2002 JR146 was 32 AU within the 30-52 AU range predicted. Also the peak of the inclination distribution (Plot B) matched the known value of 13.1°. The semi-major axis vs eccentricity plot (Plot C), also encompasses the TNO's semi-major axis of 53.97 AU and eccentricity 0.38.

As this candidate has orbits with semi-major axis > 30 AU and eccentricity < 0.4 and thus 2002 \( JR_{146} \) is correctly identified as a TNO and would be given a high priority for follow-up.
Figure 4.12: The orbital parameters fitted to TNO, 2002 JR$_{136}$. In each plot the true orbital parameter is marked with a black square, offset on the y-axis as required for clarity. The Earth-object histogram (Plot A), accurately predicts that the object is between 30 and 50 AU of the Earth. The peak of the inclination distribution (Plot B) matches the known inclination while the semi-major axis vs eccentricity plot (Plot C) also encompasses the true values.
4.12 Candidate 11

Candidate 11 was observed on the 19th, 20th and 21st April, 2002 at 6° from opposition and 5° north of the ecliptic. The object was detected with a magnitude $m_R \sim 20.4$, which was bright enough that the object was detected in all but the final blue image. Comparing the object’s positions with known positions found a match to the scattered TNO, 1996 $GQ_{21}$.

<table>
<thead>
<tr>
<th>MJD</th>
<th>Seeing</th>
<th>$m_R$</th>
<th>$m_V$</th>
<th>RA</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>52383.70889</td>
<td>1.90</td>
<td>20.36</td>
<td>21.27</td>
<td>14:12:25.44</td>
<td>-08:23:54.5</td>
</tr>
<tr>
<td>52385.60091</td>
<td>2.83</td>
<td>20.50</td>
<td>-</td>
<td>14:12:16.82</td>
<td>-08:23:00.3</td>
</tr>
</tbody>
</table>

Table 4.11: Details of Candidate 11

Figure 4.13: The orbital parameters fitted to 1996 $GQ_{21}$. In each plot the true orbital parameter is marked with a black square, offset on the y-axis as required for clarity. The histogram of the Earth-object distance (Plot A) predicts a range between 36 and 57 AU. The inclination distribution (Plot B) has two peaks at $\sim 2°$ and $\sim 13°$, the latter of which matches the known inclination, while the semi-major axis vs eccentricity plot (Plot C) also encompasses the known values.
4.13. CANDIDATE 12

As shown in Figure 4.13, 1996 GQ$_{21}$ was successfully fitted as a TNO even though it is highly eccentric. The Earth-obj distance histogram (Plot A) predicts a distance between 36 and 57 AU encompassing the true distance of 38.5 AU. The inclination distribution (Plot B) has a peak at 1$^\circ$ and $\sim$ 12$^\circ$, matching the true value of 13.3$^\circ$. In the semi-major axis vs eccentricity plot (Plot C), the semi-major axis of 94.4 and eccentricity 0.59 also lie within the predicted values.

As valid orbits were found for this candidate with semi-major axis $> 30$ AU and eccentricity $< 0.4$, it was correctly identified as a TNO and given a high priority for follow-up.

4.13 Candidate 12

This candidate was observed on the nights of July 31st, August 2nd and 3rd, 2002 at 19$^\circ$ degrees from opposition and 4$^\circ$ south of the ecliptic. The red and blue images of the first observation were found to be distinct and clearly moving while the poor seeing of the second observation smeared out the objects in both images. However, third observation the object was clearly non-stellar indicating this object had a high proper motion.

<table>
<thead>
<tr>
<th>MJD</th>
<th>Seeing</th>
<th>$m_R$</th>
<th>$m_V$</th>
<th>RA</th>
<th>Dec</th>
</tr>
</thead>
</table>

Table 4.12: Details of Candidate 12

The orbit fitting software found only 486 of 50000 attempts resulted in valid orbits. The Earth-obj distance histogram (Plot A of Figure 4.14) predicts that the candidate was within 1 AU of the Earth at the time the observations were taken. The inclination distribution (Plot B) has a peak at 2$^\circ$ while the semi-major axis vs eccentricity plot (Plot C) shows that for eccentricity $< 0.4$, the candidate has a semi-major axis $< 1$ AU. As a result this candidate is either a nearby object on an unusual orbit or a coincidental alignment of detections from 2 or more asteroids.

As this candidate only had valid orbits with semi-major axis $< 10$ AU, this object is classified as an asteroid and given a low priority for follow-up.
Figure 4.14: The orbital elements fitted to Candidate 12 by the orbit fitting software. According to the Earth-obj histogram (Plot A), the object was < 1 AU from the Earth at the time of the observations while the inclination distribution (Plot B) peaks at ~ 2°. The semi-major axis vs eccentricity plot (Plot C) suggests, for eccentricity < 0.4, the semi-major axis is < 1 AU.
Candidate 13

Candidate 13 was observed on August 10th and 13th, 2002, at 1° from opposition and 4° south of the ecliptic, with a magnitude of $m_R \sim 19.5$. It appears extended in the second and third observations. For the second observation, poor seeing meant that the shapes are still consistent with a stellar PSF. However, in the third observation, it is clearly non-stellar, which could indicate a high proper motion.

<table>
<thead>
<tr>
<th>MJD</th>
<th>Seeing</th>
<th>$m_R$</th>
<th>$m_V$</th>
<th>RA</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>52496.61152</td>
<td>3.03</td>
<td>19.52</td>
<td>20.37</td>
<td>21:24:24.96</td>
<td>-19:30:00.7</td>
</tr>
<tr>
<td>52496.74576</td>
<td>4.29</td>
<td>19.84</td>
<td>-</td>
<td>21:24:25.44</td>
<td>-19:29:51.4</td>
</tr>
<tr>
<td>52499.57626</td>
<td>2.08</td>
<td>20.27</td>
<td>20.96</td>
<td>21:24:40.03</td>
<td>-19:28:13.0</td>
</tr>
</tbody>
</table>

Table 4.13: Details of Candidate 13

Figure 4.15: The orbital elements fitted to Candidate 13 by the orbit fitting software. The Earth-obj histogram (Plot A) suggests that this candidate was within 1 AU of the Earth during the observations. The peak of the inclination distribution (Plot B) occurs at $\sim 2°$ while the plot of the semi-major axis vs eccentricity (Plot C), constrains the semi-major axis to be less than 1 AU for all orbits with eccentricity < 0.6.
The plots in Figure 4.15 generated for this candidate show that only a few valid orbits were found. The Earth-obj histogram (Plot A) suggests that this object was within 1 AU of the Earth during the observations. The peak of the inclination distribution (Plot B) occurs at \( \sim 2^\circ \) while the semi-major axis vs eccentricity plot (Plot C) shows that for eccentricity \(< 0.4\), semi-major axis \(< 1\) AU. As was the case for candidate 12, this candidate is either a nearby object on an unusual orbit or a coincidental alignment of detections from 2 or more asteroids.

As this candidate only had valid orbits with semi-major axis \(< 10\) AU, this object is classified as an asteroid and given a low priority for follow-up.

### 4.15 Summary

As shown in Table 4.14, of the 13 potential TNO candidates extracted by the data reduction pipeline and confirmed by eye, 5 of these candidates were found to be new asteroids or coincidental matches by the orbit fitting software and were given a low priority for follow-up. Two of the candidates were found to be potential centaurs or unusual TNOs and thus were given a medium priority for follow-up. The remaining 6 candidates were all found to have valid TNO-like orbits and were given a high priority for follow-up. Of these 6 TNO candidates, 3 are serendipitous recoveries of previously detected TNOs. As these are the only known TNOs in the data bright enough to be detected and they were all successfully extracted, this is a strong indication that the data reduction pipeline and orbit fitting software are powerful tools for finding TNOs.

<table>
<thead>
<tr>
<th>No.</th>
<th>MJD</th>
<th>RA</th>
<th>Dec</th>
<th>( m_R )</th>
<th>Classification</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>51689.46617</td>
<td>14:23:09.00</td>
<td>-14:56:03.0</td>
<td>18.8</td>
<td>new TNO</td>
<td>High</td>
</tr>
<tr>
<td>2</td>
<td>51689.52686</td>
<td>14:58:17.88</td>
<td>-15:26:39.4</td>
<td>20.4</td>
<td>new TNO</td>
<td>High</td>
</tr>
<tr>
<td>3</td>
<td>52025.38780</td>
<td>10:24:51.46</td>
<td>+07:57:32.3</td>
<td>19.7</td>
<td>1999 ( DE_3 )</td>
<td>High</td>
</tr>
<tr>
<td>4</td>
<td>52046.58975</td>
<td>19:21:25.25</td>
<td>-19:57:01.0</td>
<td>18.1</td>
<td>new Centaur</td>
<td>Medium</td>
</tr>
<tr>
<td>5</td>
<td>52046.63411</td>
<td>19:37:51.24</td>
<td>-25:03:40.6</td>
<td>19.5</td>
<td>new Asteroid</td>
<td>Low</td>
</tr>
<tr>
<td>6</td>
<td>52050.71759</td>
<td>19:45:15.98</td>
<td>-20:38:52.6</td>
<td>19.9</td>
<td>new Asteroid</td>
<td>Low</td>
</tr>
<tr>
<td>7</td>
<td>52052.64610</td>
<td>19:57:50.02</td>
<td>-19:01:58.4</td>
<td>19.9</td>
<td>new Asteroid</td>
<td>Low</td>
</tr>
<tr>
<td>8</td>
<td>52054.66720</td>
<td>20:09:27.50</td>
<td>-23:06:48.0</td>
<td>19.2</td>
<td>new TNO</td>
<td>High</td>
</tr>
<tr>
<td>9</td>
<td>52074.71635</td>
<td>21:13:59.33</td>
<td>-14:57:46.9</td>
<td>19.3</td>
<td>new Centaur</td>
<td>Medium</td>
</tr>
<tr>
<td>10</td>
<td>52376.72223</td>
<td>14:15:42.70</td>
<td>-19:50:10.1</td>
<td>20.5</td>
<td>2002 ( JR_{146} )</td>
<td>High</td>
</tr>
<tr>
<td>11</td>
<td>52383.70889</td>
<td>14:12:25.44</td>
<td>-08:23:54.5</td>
<td>20.4</td>
<td>1996 ( GQ_{21} )</td>
<td>High</td>
</tr>
<tr>
<td>12</td>
<td>52486.82208</td>
<td>21:59:12.72</td>
<td>-16:43:29.5</td>
<td>18.1</td>
<td>new Asteroid</td>
<td>Low</td>
</tr>
<tr>
<td>13</td>
<td>52496.61152</td>
<td>21:24:24.96</td>
<td>-19:30:00.7</td>
<td>19.5</td>
<td>new Asteroid</td>
<td>Low</td>
</tr>
</tbody>
</table>

Table 4.14: A table of the results of the 13 potential TNOs. The table consists of the candidate number, the modified Julian date of the first observation, the RA and Dec of the object at first observation, the average red magnitude, the classification according the the valid orbits from the orbit fitting software and the resulting priority.

Of these 13 candidates, only candidate 1 has had an initial set of follow-up
observation taken. These follow-up observations covered the region of sky where the candidate was predicted to be, if it was a TNO with eccentricity < 0.4, by propagating the orbits fit by the orbit fitting software. Analysis of these observations failed to detect the candidate which suggests that either this candidate is a highly eccentric TNO, as are the recovered TNOs, or is not an outer solar system body.
Chapter 5

Analysis

“Their understanding
Begins to swell and the approaching tide
Will shortly fill the reasonable shores
That now lie foul and muddy.”
William Shakespeare

5.1 Introduction

Despite over a decade of observations and analysis, there remain many open questions about the nature of the EKB. Fundamental physical characteristics such as the size and radial distribution are still not well understood. The mass of the EKB, both at the time it was formed and in its present state, is not well constrained. The composition of TNOs also remains in dispute. Even less is known about the Centaur population and its relationship to both TNOs and short-period comets. In order to build realistic models of the formation and evolution of the solar system all of these questions must be answered.

In this chapter I construct the TNO and Centaur cumulative luminosity function (CLF) obtained from the three serendipitously detected TNOs, the 3 new TNO candidates and the 2 new Centaur candidates found by our Survey, and compare it to the CLF as determined by previous surveys. Also in this chapter is a discussion of the range of observed colours for our 8 outer solar system objects.

5.2 Limiting Magnitude Achieved

Following the method of previous authors, who determined their detection efficiency by inserting synthetic images of TNOs randomly in their data and then recovering them (Luu and Jewitt. 1998; Trujillo and Jewitt. 1998; Gladman et al., 1998; Rousselot et al., 1999; Larsen et al., 2001; Millis et al., 2002; Bernstein et al., 2004), the limiting magnitude for our survey was extracted from the recovery of TNO-like objects added from our synthetic population of outer solar system bodies. These TNO-like objects were defined to be those objects which have a semi-major axis > 30AU, perihelion > 25AU, inclination < 30° and had
5.2. LIMITING MAGNITUDE ACHIEVED

a maximum change in both the red and blue magnitude < 3, and which were added to all three observations of a field as described in Section 3.6.

Typically 2-5 TNO-like synthetic objects were added per field at a range of magnitudes, $m_R = 17.5 - 23$, such that the efficiency of recovering these objects should be a true reflection of the detection efficiency for real TNOs.

Shown in Figure 5.1 is the detection efficiency for our Survey based on the synthetic TNOs added to the 1998 observed fields. Also shown in this figure is a fit to the data given by the hyperbolic tan function (Trujillo et al., 2000),

$$
\epsilon = \frac{\epsilon_{\text{max}}}{2} \left[ \tanh \left( \frac{m_{R50} - m_R}{\sigma} \right) + 1 \right]
$$

In Equation 5.1, the limiting red magnitude, $m_{R50}$ is the brightness where the efficiency, $\epsilon$, is 50% of $\epsilon_{\text{max}}$ which is defined as the maximum detection efficiency obtained for the bright objects and $\sigma$ is the magnitude range over which the efficiency drops from $\epsilon_{\text{max}}$ to zero. For the best-fit function plotted in Figure 5.1, $\epsilon_{\text{max}} = 0.746$, $\sigma = 0.6$ and the limiting magnitude of the Survey is $m_{R50} = 19.5$. This limiting magnitude is comparable to similar wide-area surveys shown in Table 5.2.

Table 5.1: The limiting magnitudes and sky coverage of selected wide-area surveys.

<table>
<thead>
<tr>
<th>Survey</th>
<th>$m_{R50}$</th>
<th>Area (deg$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Tombaugh, 1929)</td>
<td>15.5</td>
<td>~19500</td>
</tr>
<tr>
<td>(Kowal et al., 1979)</td>
<td>18.5</td>
<td>6400</td>
</tr>
<tr>
<td>(Sheppard et al., 2000)</td>
<td>18.8</td>
<td>1428</td>
</tr>
<tr>
<td>(Luu and Jewitt, 1988)</td>
<td>19.5</td>
<td>297</td>
</tr>
<tr>
<td>The SEK Survey</td>
<td>19.5</td>
<td>996</td>
</tr>
<tr>
<td>(Larsen et al., 2001)</td>
<td>20.0$^a$</td>
<td>522</td>
</tr>
<tr>
<td>(Trujillo et al., 2001a)</td>
<td>21.1</td>
<td>164</td>
</tr>
<tr>
<td>(Ivezić et al., 2001)</td>
<td>21.5</td>
<td>500</td>
</tr>
<tr>
<td>(Luu and Jewitt, 1998)</td>
<td>26.1</td>
<td>1007</td>
</tr>
</tbody>
</table>

$^a$ Converted to R magnitude under the assumption V-R = 0.5.

Even though our measured limiting magnitude is within the range of other surveys, our expectation when the survey began was that our automated search algorithm would successfully extract all bright TNOs. However, as shown in Figure 5.1, our efficiency was at most 75% for the bright objects. To track down where in the pipeline our synthetic objects were being lost, all added TNO-like synthetic objects with an average magnitude over the three observations $m_R < 19$, was selected to be investigated. This sample contained 200 synthetic objects of which 132 were found successfully while 67 failed to be recovered, with their reasons for failing listed in Table 5.2. It should be noted that in all but a few cases the lost objects were successfully recovered in two observations, but for an object to be 'found' it must be recovered in all three observations.
Figure 5.1: A histogram of the fraction of the total survey sensitive to TNOs of a given magnitude based on the synthetic population of TNOs. This plot reflects the fraction of real TNOs which could have been discovered by the Survey. The points denote the fraction of synthetic TNOs recovered in each magnitude bin with a fit to the hyperbolic tangent efficiency function (solid line).
Table 5.2: A list of the reasons why a synthetic TNO failed to be recovered and the number of objects affected in each case.

<table>
<thead>
<tr>
<th>Reason for failure</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor background level input to DoPHOT</td>
<td>17</td>
</tr>
<tr>
<td>Software timed out</td>
<td>12</td>
</tr>
<tr>
<td>Not added despite entry in log</td>
<td>8</td>
</tr>
<tr>
<td>Object fell on star</td>
<td>6</td>
</tr>
<tr>
<td>Fitted magnitude error too large</td>
<td>4</td>
</tr>
<tr>
<td>Bad amp in chip 1</td>
<td>2</td>
</tr>
<tr>
<td>Failed Direction cut</td>
<td>8</td>
</tr>
<tr>
<td>Failed Magnitude cut</td>
<td>3</td>
</tr>
<tr>
<td>Failed Angle cut</td>
<td>2</td>
</tr>
<tr>
<td>Failed Maximum Velocity cut</td>
<td>1</td>
</tr>
</tbody>
</table>

Looking at the reasons for losing synthetic TNOs shown in Table 5.2 there are clearly several areas which could be improved to increase the overall detection efficiency. The bulk of objects failed because in at least one observation, the measured sky background input into DoPHOT was incorrect, usually resulting in no objects being extracted. In most cases the measured sky background was incorrect because the field was affected by a very bright star which significantly increased the background, or the field was very crowded so that there were few pixels containing only background light. As typically no objects were extracted and hence there was no possibility of finding moving objects, such images could be removed from the survey region. In most cases only 1 or 2 chips were affected so that only a small area (and not the entire field) would need to be removed. This is also the case for the known problem of the failing amp in Chip 0. If the fields with this problem are identified they could also be removed from the survey area.

The second largest loss of synthetic objects occurred because several key programs making up the pipeline were only allowed to run for a maximum of 40 minutes. This time constraint was necessary since there was a limited amount of computer time and a need to process as many fields as possible. In most cases the programs finished well within this time constraint but crowded fields and fields which had one or more observations taken with poor seeing could require several hours to complete their analysis. In all 12 cases the objects would have been successfully extracted if given enough processing time.

Also shown in Table 5.2, a number of synthetic TNOs were lost because they were written to a log file as being added when an inspection of the image found that there was no object at the required position. This most likely points to there being a problem in adding a small fraction of synthetic objects. As a result these objects were counted as being added during the calculation of the detection efficiency, even though there was no possibility of their being found, and could cause the detection efficiency to be underestimated by $\lesssim 4\%$ across the entire range of magnitudes.

The last 4 reasons for a lost TNO listing in Table 5.2 relate to the TNO
search algorithm. In these cases the synthetic TNOs were recovered in all three observations but failed 1 or more selection criteria cuts and were rejected as possible TNOs. In each case the criteria could be slackened or removed (as in the case of the direction cut) but this would significantly increase the number of spurious objects requiring a human check.

If the problems discussed above were remedied and the analysis pipeline rerun on the data the detection efficiency for objects with \( m_R < 19 \) could rise up to \( \sim 83\% \).

### 5.3 The TNO Cumulative Brightness Function

Two of the remaining open questions about the EKB are the features of its size and distance distributions. Understanding the size distribution is important because it may reflect the conditions in which TNOs grew (Stern and Colwell, 1997) as well as the role of collisions in shaping the EKB (Farinella and Davis, 1996). The distance distribution contains additional information about accretion and the processes that were important in the dynamical evolution of the EKB after its formation (Holman and Wisdom, 1993; Duncan et al., 1995; Malhotra, 1996).

With the inclusion of a few assumptions, both the size and distance distributions can be extrapolated from the cumulative apparent brightness function, commonly known as the cumulative luminosity function (CLF). The CLF describes the sky-plane surface density of objects brighter than a given magnitude within a degree of the ecliptic. The advantage of calculating the CLF is that it is relatively assumption free and is based solely on the Survey’s observations.

The CLF is fitted by a power law of the form

\[
\log \Sigma = \alpha (m_R - m_0), \tag{5.2}
\]

where \( \alpha \) describes the slope and \( m_0 \) is the red magnitude at which \( \Sigma = 1 \) TNO deg\(^{-2} \).

Currently, as a result of work by several surveys, the magnitude region between \( 21 < m_R < 27 \) appears to be well constrained (Jewitt et al., 1998). As given in Schulz (2002) and reproduced here the commonly accepted range of values for the parameters \( \alpha \) and \( m_0 \) are given in Table 5.3. (Larsen et al., 2001). However, very few TNOs fainter than \( m_R \sim 27 \) or brighter than \( m_R \sim 21 \) have been detected. Most of the surveys in these regions have only been able to provide upper limits to

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>( m_0 )</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.55 ± 0.05</td>
<td>23.25 ± 0.11</td>
<td>(Jewitt and Luu, 1998)</td>
</tr>
<tr>
<td>0.76(^{+0.11}_{-0.11})</td>
<td>23.40(^{+0.20}_{-0.18})</td>
<td>(Gladman et al., 1998)</td>
</tr>
<tr>
<td>0.52 ± 0.02</td>
<td>23.5 ± 0.06</td>
<td>(Chiang and Brown, 1999)</td>
</tr>
<tr>
<td>0.59 ± 0.05</td>
<td>23.0 ± 0.2</td>
<td>(Sheppard et al., 2000)</td>
</tr>
<tr>
<td>0.69</td>
<td>23.5</td>
<td>(Gladman et al., 2001)</td>
</tr>
</tbody>
</table>
The CLF, hence the current available data are equally consistent with a constant slope as with a steepening of the luminosity function at the bright end of the CLF (Schulz, 2002).

The CLF is a measure of the surface density of TNOs in the ecliptic, and as a result surveys have traditionally limited their search region to fields within a degree of the ecliptic. Calculating the CLF in the region of the ecliptic is a good choice because even TNOs with relatively high inclinations \((i < 30^\circ)\) spend some fraction of their orbit on the ecliptic. A drawback of this convention is that surveys conducted in this region are strongly biased towards finding only low inclination TNOs as this is where these objects spend the bulk of their orbit. On the other hand, while taking observations at higher latitudes covers more of the region where higher inclination TNOs are likely to be, TNOs with inclinations less than the observed ecliptic latitude cannot be observed.

![Figure 5.2](image.png)

Figure 5.2: This figure shows the fraction of TNOs at each \(\beta\) for TNOs with inclinations of 0\(^\circ\) (solid line), 5\(^\circ\) (dashed line) and 10\(^\circ\) (dot-dash line). This histogram is equivalent to the fraction of time that a TNO with each inclination would spend at each latitude.

Figure 5.2 demonstrates how a TNOs distance from the ecliptic is strongly dependent on its inclination. It illustrates that, as expected, TNOs with incli-
nations less than 1° spend more than 95% of their orbit within a degree of the ecliptic while TNOs which are inclined at 10° are found within the ecliptic for less than 0.5% of their orbit.

As more than half of our observations were taken off the ecliptic, in order to calculate the CLF, we need to correct the survey region by converting it to the equivalent region which would have been covered if it had only been taken within a degree of the ecliptic. The correction, $\zeta$, is dependent on the fraction of fields observed at each latitude, the fraction of TNOs which could be seen at each latitude relative to the fraction seen at the ecliptic ($\beta = 0$) and the TNO inclination distribution. To simplify the calculations we bin our survey into 1° bins for both inclination, $i$, and ecliptic latitude, $\beta$, and then the correction, $\zeta$, is determined by:

$$\zeta = \frac{\sum_{i=0}^{30} \sum_{\beta=0}^{10} F_\beta \times S_{i\beta} \times I_i}{\sum_{i=0}^{30} \sum_{\beta=0}^{10} F_\beta \times I_i}$$  \hspace{1cm} (5.3)$$

where $F(\beta)$ is the fraction of the survey observed at an ecliptic latitude, $\beta$ and $S(i, \beta)$ is the fraction of time that a TNO of inclination $i$ spends at ecliptic latitude $\beta$ relative to the fraction of time that the same TNO would spend on the ecliptic. The TNO inclination distribution, $I(i)$, for the entire TNO population has been found to be well fit by the product of $\sin i$ multiplied by the sum of two Gaussians as determined by Brown (2001):

$$I_i = \sin(i) \left[ a e^{-\frac{i^2}{2\sigma_1^2}} + (1-a) e^{-\frac{i^2}{2\sigma_2^2}} \right]$$  \hspace{1cm} (5.4)$$

Where $a = 0.83 \pm 0.003$, $\sigma_1 = 2.6^{+0.8}_{-0.2}$ and $\sigma_2 = 15 \pm 1$.

Using these functions, the correction factor for our survey region was determined to be $\zeta = 0.449$. In order to test how strongly the choice of inclination distribution influences the correction factor, the calculation for $\zeta$ was repeated using both a flat distribution ($I_i = 1$) and an inclination distribution of the form commonly used for plutinos, which typically have higher inclinations than classical TNOs. The plutino inclination distribution has been found to be well described by a sin function multiplied by a single Gaussian of the form

$$I_i = \sin(i) e^{-\frac{i^2}{2\sigma^2}}$$  \hspace{1cm} (5.5)$$

(Brown, 2001). Here $\sigma = 10.2^{+2.5}_{-1.8}$.

Table 5.4: The correction factor based on 3 different inclination distributions.

<table>
<thead>
<tr>
<th>Inclination Distribution</th>
<th>$\zeta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All TNOs</td>
<td>0.449</td>
</tr>
<tr>
<td>Plutinos</td>
<td>0.499</td>
</tr>
<tr>
<td>Flat</td>
<td>0.508</td>
</tr>
</tbody>
</table>

As shown in Table 5.4, for a flat inclination distribution the correction factor was 0.508 while employing the plutino inclination distribution resulted in a correction factor of 0.499.
Since these three values all agree to within $\sim 10\%$, it can be concluded that this factor is not strongly dependent on the choice of inclination distribution, and $\zeta = 0.449$ was chosen to correct the survey region.

Table 5.5: Summary of Cumulative sky densities for TNOs in the Survey

<table>
<thead>
<tr>
<th>$m_R$</th>
<th>TNOs</th>
<th>Area $(deg^2)$</th>
<th>$N/Area \ (N_{deg^{-2}})$</th>
<th>$\Sigma(&lt; m_R) \ (N_{deg^{-2}})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.75</td>
<td>$1 \pm 1$</td>
<td>276.1</td>
<td>0.004 $\pm$ 0.004</td>
<td>0.004 $\pm$ 0.004</td>
</tr>
<tr>
<td>19.25</td>
<td>$1 \pm 1$</td>
<td>209.4</td>
<td>0.005 $\pm$ 0.005</td>
<td>0.009 $\pm$ 0.006</td>
</tr>
<tr>
<td>19.75</td>
<td>$1 \pm 1$</td>
<td>142.3</td>
<td>0.007 $\pm$ 0.007</td>
<td>0.016 $\pm$ 0.009</td>
</tr>
<tr>
<td>20.25</td>
<td>$3 \pm \sqrt{3}$</td>
<td>51.0</td>
<td>0.058 $\pm$ 0.033</td>
<td>0.060 $\pm$ 0.035</td>
</tr>
</tbody>
</table>

Shown in Table 5.5 are the effective area and the CLF for the 3 recovered TNOs and 3 candidate TNOs found by our survey, assuming Poisson statistics. A comparison of our values for the CLF with other surveys is shown in Figure 5.3.

As shown in Figure 5.3, our calculation of the CLF is within the errors quoted by several surveys. The best fit to our data was determined to be $\alpha = 0.756$ and $m_0 = 21.96$. If we compare our fits to those listed in Table 5.5, we find that this fit has a similar slope to those quoted by other authors, but our $m_0$ is more than a magnitude brighter. This is most likely the result of the method by which we determined our sky coverage and detection efficiency. As noted above, even fields observed less than 2 degrees away from the ecliptic require some correction and as a result, surveys which do not make this correction because their observations are close to the ecliptic could be underestimating the CLF. It is also probable that our current estimates of the detection efficiency underestimate the true recovery rate. An improved detection efficiency should have the effect of lowering our calculated CLF but keeping the slope the same, and this would bring our results into very close agreement with the values listed in Table 5.5.

Another possibility is that one or all of our three TNO candidates is not a true outer solar system object as these candidates have yet to be confirmed by recovery observations. The result of removing these candidates from our calculations is that the first three points become upper limits, which would make the fit to the CLF difficult to determine.

The final most likely possibility is that our values for the CLF are correct. Few surveys have conducted dedicated searches for TNOs brighter than $m_R \sim 20$ and as a result almost all measurements for the CLF in this region are only upper limits. It is possible that our data are suggesting that for $m_R < 20$, the CLF has a shallower slope, a result which would have several implications for the growth of bodies in the outer solar system.
Figure 5.3: The CLF calculated from the total sky coverage at each magnitude bin, corrected for fields observed away from the ecliptic and using the 6 TNO candidates which is overlaid on measurements of the CLF from surveys by Trujillo et al. (2001a), Ferrin et al. (2001), Larsen et al. (2001), Sheppard et al (2000), Jewitt, Luu & Trujillo (1998), Kowal (1989), Luu & Jewitt (1988) and Tombaugh (1929). Figure adapted from Trujillo et al. (2001a).
5.4 Centaur Cumulative Brightness Function

Centaurs are a class of outer solar system bodies which lie on dynamically unstable orbits in the region between Jupiter and Neptune. They appear to have intermediate sizes between comets (diameter ~ 1 – 20 km) and the largest TNOs (diameter < 2300 km). The first centaur, Chiron, was discovered in 1979 (Kowal et al., 1979) when it was initially classified as a comet. Another 15 years passed before the second Centaur, Pholus was discovered (Scotti et al., 1992) and at present approximately 100 centaurs have been identified and recorded at the MPC.

Centaurs are distinguished by their dynamical lifetimes, typically surviving the chaotic region between the planets for $10^5$ – $10^7$ years, which is relatively short when compared with the age of the solar system (Hahn and Bailey, 1990; Holman and Wisdom, 1993; Levison and Duncan, 1997). For Centaurs to still exist implies that a reservoir of bodies must be continually replenishing the Centaur population with the EKB the most obvious choice.

Studies of Centaurs have shown that they have photometric colours similar to that of TNOs, with Chiron at one extreme being very neutral to Pholus at the other extreme measured to be the reddest body in the solar system (Luu and Jewitt, 1996; Romanishin et al., 1997; Davies et al., 1998). Observations of Chiron also appear to show comet-like activity (Tholen et al., 1988; Meech and Belton, 1989; Meech and Belton, 1990).

Taken together, this evidence suggests that TNOs, Centaurs and Jupiter-family comets are different evolutionary stages for the same population of minor planets in the outer solar system. In this scenario, TNOs are perturbed towards the inner solar system due to the influence of the giant planets or as a result of collisions (Stern, 1995; Duncan et al., 1995; Stern and Campins, 1996) to become the population of Centaurs. The Centaurs then experience successive interactions with the major planets where they can be captured or ejected from the solar system (Bauer et al., 2003) while Centaurs which survive the passage through the inner solar system can then develop comae and evolve into Jupiter-family comets (Levison and Duncan, 1997).

Recently, dynamical simulations of the evolution of the outer solar system have confirmed the EKB as the source of Centaurs, providing the first step for a theoretical foundation to the link between TNOs, Centaurs and short-period comets (Duncan et al., 1987; Duncan et al., 1988; Holman and Wisdom, 1993; Levison and Duncan, 1993; Levison and Duncan, 1997; Duncan and Levison, 1997; Morbidelli and Valsecchi, 1997).

Early work by Jedicke & Herron (1997) demonstrated that the observed number of Centaurs may represent less than 10% of the total population. In order to obtain a better estimate of the Centaur population we used our 2 possible Centaur detections and the Survey’s sensitivity for detecting such objects to construct the Centaur CLF.

Our sensitivity to Centaurs was determined in the same manner as the calculation for the Survey’s sensitivity to TNOs, by using the synthetic population of outer Solar System bodies. For this calculation a Centaur was defined to be all objects with semi-major axis < 30 AU, with all other orbital parameters allowed
to span the entire range. As Centaurs are often on chaotic and rapidly evolving orbits, this broad definition allows a wide range of possible Centaur orbits to be probed.

Figure 5.4: Histogram of the sensitivity of the Survey to discovering Centaurs. The fraction is quite low because the TNO search algorithm is not optimized for detecting objects less than 30 AU from the Sun.

As shown in Figure 5.4, the Survey’s overall sensitivity is not high, with the detection efficiency reaching no more than 35% even for the brightest Centaurs. This poor sensitivity to Centaurs is the result of the TNO search algorithm being optimized for objects with semi-major axis > 30AU and is thus designed to systematically reject both asteroids and Centaurs.

In order to calculate the Centaur CLF, the 2 Centaur candidates are placed in 1 magnitude wide bins and divided by the effective area observed at each magnitude. The effective area was determined in the using the same method as for the TNO effective area which was to take the entire survey region, correct it by \( \zeta = 0.449 \), to account for observations taken far from opposition and then multiply it by the sensitivity in each bin as given in Figure 5.4. The resulting effective area and CLF are shown in Table 5.6 and plotted against other calculations of the CLF in Figure 5.5.

If we then compare our result with the CLF previously calculated for Centaurs as shown in Figure 5.5 we find that, just as in the case of the TNO CLF, our values are higher than those calculated by previous surveys but within the error bars.
Table 5.6: Summary of Cumulative sky densities for Centaurs in the Survey

<table>
<thead>
<tr>
<th>$m_R$</th>
<th>TNOs</th>
<th>Area ($\text{deg}^2$)</th>
<th>N/Area ($N\text{deg}^{-2}$)</th>
<th>$\Sigma(&lt;m_R)$ ($N\text{deg}^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.00</td>
<td>1 ± 1</td>
<td>164.7</td>
<td>0.006 ± 0.006</td>
<td>0.006 ± 0.006</td>
</tr>
<tr>
<td>19.00</td>
<td>1 ± 1</td>
<td>164.7</td>
<td>0.006 ± 0.006</td>
<td>0.012 ± 0.008</td>
</tr>
</tbody>
</table>

Figure 5.5: The Centaur CLF calculated from the total sky coverage at each magnitude bin, corrected for fields observed away from the ecliptic and using our 2 Centaur candidates shown in cyan overlaid with measurements of the CLF from surveys by Kowal (1989), Jewitt, Luu & Trujillo (1998), Gladman et al. (1998), Sheppard et al. (2000) and Larsen et al. Figure adapted from Larsen et al. (2001).

As shown in Figure 5.5, as was the case for the TNO CLF determined in the previous section, our calculated CLF values are higher than those quoted by other authors and also plotted in the figure. This could be due to the Centaur detection efficiency measured from the synthetic Centaur population not being a
true reflection of the Survey’s ability to detect Centaurs, or it may be that one or both candidates are not true Centaurs. Recovery of neither object has been attempted and until their orbits are confirmed, these values should be viewed as upper limits to the CLF. However, making any predictions about the Centaur CLF is still difficult as it is based on only a small sample of objects from a handful of surveys.

5.5 The TNO and Centaur Colour Distribution

The EKB should contain some of the least processed materials remaining from the primordial debris disk that formed the solar system (Brown et al., 2000). While populations such as asteroids have been substantially heated during and after their formation and comets are heated during their close approach to the Sun, TNOs are presumed to form far from the Sun in the outer debris disk and so should retain the overall chemical and physical conditions that were present in the early solar system.

The composition of TNOs also provides physical evidence of the evolution of TNOs into Centaurs and short-period comets (Duncan and Levison, 1997). As the bulk of TNOs are too faint to be studied spectroscopically, the only technique for studying the entire known population is by measuring their colour. As TNOs were all thought to have formed at approximately the same time and significantly far from the Sun, it was expected that they should all appear to have the same colour. However, several studies have shown that TNOs are spectrally diverse with colours ranging from neutral \((V - R \sim 0.3)\), to extremely red \((V - R \sim 0.8)\) (Jewitt et al., 2001).

As shown in Figure 5.6, several authors (Luu and Jewitt, 1996; Jewitt et al., 1998; Barucci et al., 1999; Barucci et al., 2000; Doressoundiram et al., 2002; Hainaut and Delsanti, 2002) find that the TNO and Centaur populations exhibit a relatively uniform distribution of colours, which they attribute to the competing effects of solar and cosmic radiation which has the effect of creating a dark mantle on the surface of the TNOs making their colours appear more red, and collisions which uncover the interior gray icy material in the form of craters. This process has the advantage that it can also explain why some large TNOs appear to vary in both their brightness and colour with rotation (Jewitt and Sheppard, 2002; Boehnhardt et al., 2004). A major complication of this evolutionary scenario is that the bulk of TNOs appear to have uniform surface colours (Jewitt et al., 2001).

However, this result is still in contention by Tegler and several co-authors (Tegler and Romanishin, 1998; Tegler and Romanishin, 2000; Tegler et al., 2003) who believe that their results show that the TNO colour distribution is bimodal, with the TNOs separated into a neutral or 'grey' population, which they suggest may have formed much closer to the Sun and then been ejected into the EKB, and a more red TNO population which represent the bodies originally formed in the EKB.

The issue of colour remains unresolved because only a fraction of TNOs and Centaurs have been observed in more than one colour. As the observations for
Figure 5.6: Plot of the V-R colour vs B-V colour for all three classes of TNOs and the Centaurs. The colour of the Sun is shown as an asterisk towards the bottom left of the plot (Peixinho et al., 2003).
the SEK Survey were taken simultaneously in both a red and blue filter, our candidates represent an excellent sample with which to investigate the range of colours in outer solar system objects.

The red and blue filters used by the Survey were not the standard Kron-Cousins R and V bands so the first step in determining the colour of these objects was to make the appropriate transformation to the measured red and blue magnitudes of all three observations of the candidates. This was done by following the procedure outlined in Alcock (1999) utilizing three of the four coefficients: zero point, colour coefficient and colour air-mass coefficient. The chunk offset coefficient was not used as it was of the order \(10^{-2}\) magnitudes, well below the accuracy of our measurements. In all cases, the change in the magnitude due to the transformation was < 0.25. The final step was to take the average of the three observations for both the V and R magnitudes and the V-R colour as shown in Table 5.7.

Table 5.7: Survey Candidate Colours

<table>
<thead>
<tr>
<th>Cand</th>
<th>Type</th>
<th>(\bar{m}_R)</th>
<th>(\bar{m}_V)</th>
<th>V-R</th>
<th>Measured V-R</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>new TNO</td>
<td>19.0 ± 0.1</td>
<td>19.4 ± 0.1</td>
<td>0.4 ± 0.2</td>
<td>0.58 ± 0.006 (Delsanti et al., 2001)</td>
</tr>
<tr>
<td>2</td>
<td>new TNO(^a)</td>
<td>20.6 ± 0.1</td>
<td>21.0 ± 0.1</td>
<td>0.4 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1999 DE(_9)</td>
<td>20.0 ± 0.2</td>
<td>20.7 ± 0.2</td>
<td>0.7 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>new Centaur</td>
<td>18.4 ± 0.1</td>
<td>19.0 ± 0.1</td>
<td>0.6 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>new TN0</td>
<td>19.3 ± 0.1</td>
<td>20.0 ± 0.1</td>
<td>0.7 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>new Centaur</td>
<td>19.4 ± 0.1</td>
<td>19.9 ± 0.2</td>
<td>0.5 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>2002 JR(_{146})</td>
<td>20.7 ± 0.1</td>
<td>21.1 ± 0.2</td>
<td>0.5 ± 0.2</td>
<td>0.726 ± 0.043 (Boehnhardt et al., 2002)</td>
</tr>
<tr>
<td>11</td>
<td>1996 GO(_{21})</td>
<td>20.6 ± 0.1</td>
<td>21.3 ± 0.3</td>
<td>0.7 ± 0.3</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Based on only 1 measurement  
\(^b\) Based on only 2 measurements

As shown in Table 5.7, our sample of 2 Centaurs and 6 TNOs show a broad range of colours, all of which are redder than the Sun (\(V - R = 0.36\)). Of the 3 known TNOs, 2 have colours which exist in the literature (Delsanti et al., 2001; Boehnhardt et al., 2002) and these measurements are in agreement with our colours.

Figure 5.7 is a colour-magnitude diagram displaying the measured colours of the 3 recovered TNOs, the 3 new TNO candidates and the 2 new Centaur candidates detected by the survey. This figure shows that our candidates cover a broad range of colours from neutral to red with no signs of bimodality. This figure also shows that the 2 Centaur candidates have colours very similar to our TNOs, while all candidates exhibit colours which would place them well within the range of measured colours for minor bodies. Therefore, our sample of TNOs and Centaurs would support the contention that minor planets exhibit a uniform distribution of colours as a result of the competing effects of collisions and solar radiation, and that Centaurs and TNOs are different evolutionary stages of the same primordial population of minor planets. However, a much large sample of
5.5. THE TNO AND CENTAUR COLOUR DISTRIBUTION

Figure 5.7: Plot of the V-R colour vs R for our 2 Centaurs (Cyan) and 6 TNOs (black). Our candidates show the distinctive red colour indicative of most TNOs. The dotted line marks the V-R of the Sun.

colours for Centaurs and TNOs is required before this contention can be fully resolved.
Chapter 6
Conclusions and Future Work

"Real knowledge is to know the extent of one's ignorance"
Confucius

It has been a little over a decade since the discovery of the first TNO and in that time our knowledge of the outer Solar System has been completely revised, both from an observational and theoretical point of view. However major questions still remain concerning the current structure of the EKB as well as it's formation and evolution. Perhaps, as suggested by the above quote, we are now at the stage where we can begin to understand the extent of our ignorance. The renewed interest in the Solar system, and the ever increasing technological advances in instrumentation, make the prospect of the coming decade an exciting and important one for TNO research. In this context, this chapter will summarize the main conclusions resulting from the SEK survey, and outline a few key areas for further analysis of the survey data.

6.1 Conclusions

The SEK Survey was an ambitious project to search for bright TNOs. Using the Great Melbourne Telescope at Mount Stromlo Observatory it aimed to have a large sky coverage, both on and off the ecliptic, with observations simultaneously obtained in two colours. The project also aimed to develop efficient and self-consistent methods for processing the data, searching for TNOs and calculating the detection efficiency.

The Survey operated for almost 3 years until, on January 18 2003 the telescope and computers were destroyed in a devastating fire. Despite the survey being cut short by 6 months, the Survey was able to cover more than 2000 deg$^2$ making it one of the largest TNO surveys to date, and the only one of it's kind undertaken in the southern hemisphere. The destruction of the computers meant the loss of all the processed data, which constituted almost half of the entire survey. Though this loss set the survey back more than a year, thanks to the generous assistance of staff, both at the Research School of Astronomy and Astrophysics ANU and the Astronomy department at UPenn, almost 2000 fields were able to be re-reduced and checked by eye.
6.1. CONCLUSIONS

The Survey was able to successfully determine its detection efficiency by creating a synthetic population of outer solar system bodies and developing a series of routines to add these bodies to the data, such that they appeared to be identical to real moving objects, ensuring that the data reduction was double-blind. This synthetic population was also used successfully to determine the limiting magnitude of the survey, test the analysis pipeline proficiency and examine the biases intrinsic to the survey, making it a powerful tool for internal analysis of the data.

The key component of the data reduction pipeline was the TNO search algorithm, developed by the Survey to take advantage of several unique features of the observations such as the 2 colour image information. This search algorithm, based on 7 characteristics of outer solar system bodies, was found to have an overall proficiency of recovering more than 93% of both synthetic and known TNOs in the data. For observations taken within 30° of opposition, this number rose to more than 98% of all TNO-like objects. Furthermore, the search algorithm was able to effectively identify more than 99% of asteroids and discard them as possible TNO candidates, which significantly reduces the possibility of contamination by these objects, making the search algorithm a robust discriminator between TNOs and less distant solar system bodies.

Also developed for this survey was orbit fitting software, designed to quickly determine the range of orbital parameters fitting the short arc each TNO candidate was observed on. This software is also able to define a search region in order to recover the candidates. Tests have shown that although it was originally designed for follow-up observations taken at most 1 month after the discovery observations, 92% of the synthetic TNO sample had follow-up regions which correctly enclosed their true positions even when the recovery observations were predicted to take place more than 3 years after the initial observations.

Analysis of approximately half of the observed data yielded three serendipitous recoveries of known TNOs, three potential TNO discoveries and two potential Centaur discoveries. Confirmation that the potential discoveries have been correctly classified will only come from recovery observations, which have currently only been carried out for one of the TNO discoveries. These follow-up observations ruled out the object as a low eccentricity TNO but still require further observations to determine if the object is a TNO.

Under the assumption that all the potential discoveries are correctly classified this provided a well defined sample of eight outer solar system objects with which to probe the TNO and Centaur CLF's and the colour distribution of the objects.

Our calculations of the TNO CLF gives values which are within the limits given by previous surveys in the literature, but do lie above the predicted best-fit to the data which could suggest that for $m_R < 20$ the CLF has a more shallow slope.

Our calculations for the Centaur CLF again give values which are higher than predicted but within the errors quoted in the literature. However, it is difficult to draw conclusions when all current surveys of centaurs, including the SEK survey, suffer from small number statistics.

The bi-colour nature of the observations made the 8 candidates a good sample with which to contribute to the continuing debate over the colour distribution of
both TNOs and Centaurs. A comparison with our measured colours to previous measurements of the colour of 1996 \( GQ_{21} \) and 1999 \( DE_9 \) (Delsanti et al., 2001; Boehnhardt et al., 2002) were in good agreement. The colours of the TNOs ranged uniformly from neutral, \( V-R \sim 0.4 \), to very red, \( V-R \sim 0.7 \) showing no signs of the bimodality seen by Tegler and his colleagues (Tegler and Romanishin, 1998; Tegler and Romanishin, 2000; Tegler et al., 2003) but rather a uniform distribution as seen in several other surveys (Luu and Jewitt, 1996; Jewitt et al., 1998; Barucci et al., 1999; Barucci et al., 2000; Doressoundiram et al., 2002; Hainaut and Delsanti, 2002). Our data also supports the theory that Centaurs have very similar colours to TNOs, which is expected if they are different evolutionary stages of the same primordial population of minor planets.

### 6.2 Future Work

There still remains significant potential for new discoveries and fundamental analysis of minor planets within the survey data. The first task should be to further investigate where the synthetic objects are failing to be recovered, and to make improvements both to the pipeline and to the determination of the recovery rate of the objects, with the goal of increasing the overall detection efficiency of the survey. As noted in Chapter 5, by analyzing the synthetic objects with \( m_R < 19 \), several areas where improvements could be made were identified. Early indications are that if improvements could be made, the detection efficiency could rise to more than 85% in the brightest bins.

The results presented in this thesis represent approximately half of all the observations taken by the Survey. Some of the remaining observations have been processed but have yet to be checked by eye. These remaining fields have a significantly higher number of candidates to be checked, and will require a further step to remove systematic errors which produce the higher number of spurious candidates. The remaining observations are yet to be processed through the pipeline. A major fraction of these observations are of fields observed far from the ecliptic and so are potentially the most likely fields in which a large, highly inclined TNO would be found.

It is also necessary to complete recovery observations for the 3 potential TNO and 2 potential Centaur candidates. Being able to recover the outer solar system objects from these observations will confirm the use of the orbit fitting software for this purpose, confirm their classification as either TNOs or Centaurs and provide the means for obtaining an orbit good to within an arcsecond for the next decade. Such precision is vital for the TNO candidates as they represent some of the largest detected members of the EKB and will be valuable subjects for spectroscopic studies, stellar occultations and albedo measurements. Also, with accurate classifications and orbits, this sample of objects can also assist in constraining current models of the formation and evolution of the solar system. As discussed in Chapter 4, preliminary follow-up observations of Candidate 1, our brightest TNO candidate, were taken with the 40" telescope at Siding Spring Observatory. This candidate failed to be recovered in these observations, which rules it out as a low eccentricity object, but there is still a significant region
to be observed before this object can be ruled out as a TNO, while recovery observations are yet to be carried out for the other 4 candidates.

Another key area of future research will be to modify the analysis pipeline and TNO search algorithm presented in chapter 3 so that it can be utilized by the Southern Sky Survey\(^1\). This survey, will be undertaken on a new state-of-the-art 1.3m telescope to be built in the next decade at Siding Spring Observatory, Coonabarabran. It is an ambitious project which aims to cover the entire southern sky with repetitive observations in order to search not only for TNOs but also many other astronomically interesting transient objects including Near-Earth Asteroids, Centaurs, variable stars, supernovae and gamma ray bursts.

Given the recent discoveries of bright TNOs such as Quaoar and Sedna, and the results of this survey which indicate that the CLF at the bright end \((m_R < 20)\) is potentially more shallow than previously measured, it is timely to review models of the dynamical effects a primordial population of Charon- to Pluto-sized bodies would have on the structure of the EKB. Utilizing the method of symplectic mapping, these large TNOs could represent a perturbing force to the primary gravitational influence of the Sun and the major planets. Such a model could investigate the higher than expected range of inclinations for TNOs, the missing mass beyond 50 AU and whether interactions with a population of large TNOs influences the rate at which Centaurs are ejected into the inner solar system.

\(^1\)http://www.mso.anu.edu.au/skymapper/survey.html
Appendix A

TNO Scheduler

A scheduler, written in PERL, is queried by the telescope before every observation. This scheduler makes a series of cuts to determine a set of fields which are available to be observed and then prioritizes this set according to several criteria in order to determine the optimum field to be observed at that time. In more detail the steps of the Scheduler include:

1. All fields further than 40° in R.A. away from opposition are excluded. This is to avoid the quadrature points of asteroids, which occurs at ±45° from opposition, where their apparent motion is slow enough that they can be mistaken for more distant bodies.

2. All fields within a maximum distance of the moon are excluded. This maximum distance depends only on the fraction of the moon illuminated.

3. Fields which have been observed less than 3 hours ago or more than 7 days ago are excluded.

4. All fields with positions which would cause the telescope to trip it's hardware limits are excluded.

5. Fields which have been previously observed and can only be observed on the opposite pier side to their original observations are excluded unless the field cannot have it's observations completed otherwise. Having observations of a field on both sides of the pier results in different parts of the red and blue CCDs aligning which makes data reduction more difficult and hence the lower priority. The possibility of observing on a different side of the pier is included so that a larger fraction of fields have their observations completed.

6. In the final 3 hours of observing each night, fields which have not yet been observed are excluded unless there are no other fields to observe.

The fields remaining after these cuts are then prioritized according to criteria such as the time since last observation, distance of the field from the zenith and the fields distance from opposition. The highest priority field is then chosen for the next observation. In more detail each field’s priority is determined by:
1. Fields are given an initial priority if they have been observed previously.

2. Fields are then given a priority (or an increased priority) if they are due to set within the first two hours of each night. This allows fields which are only visible for a few hours not to be neglected.

3. Fields have their priority increased if they have not been observed previously but border a field which has. This allows a larger continuous area of sky to be covered each night which increases the chances of finding a TNO which has moved from one field to another over the course of the observations. It also minimizes the time lost due to repositioning the telescope.

4. The scheduler is heavily biased toward completing the observations for a given field once the initial observation has been taken. This is reflected in the field's priority which is exponentially increased according to the number of hours since the field was last observed after the enforced 3 hour gap.

5. To favour observations being taken where the airmass is lowest and the seeing is best, the fields near the zenith are weighted slightly higher than the fields which are further away.

6. Fields then have their priorities increased by their zone (see Figure A.1) such that fields within 1.5° of the ecliptic are 5 times more likely to be observed than fields which are 20° away.

Figure A.1: Fields observed from Jan 1, 2000 to Nov 30, 2002
7. The priorities of all fields are then quadratically biased toward the fields closest to opposition. This is to ensure that only fields where the angular motion of a TNO is entirely dependent on the Earth's motion are observed.
Appendix B

Candidate Images

Figure B.1: Each of the 3 mosaiced images show distinct objects in both the red and blue detection images which have clearly moved when compared to the same area of sky in the red and blue reference images. The detections from observations 1 and 3 are distinct and point-like while the detection of the candidate in the 2nd observation appears a slightly extended in both the red and blue images as a result of the poor seeing during the observation (see Table 4.1).
Figure B.2: The candidate was successfully recovered in all three red images but was only found in the blue image of the first observation. The object was too faint and smeared to be recovered in the 2nd observation and failed to be found in the 3rd observation because of problems reading the ccd (hence the horizontal lines in the mosaic). However, to the eye all objects are present in both the red and blue images.

Figure B.3: The candidate is on the threshold of detection but was successfully found by the analysis software in both the red and blue images of each observation.
Figure B.4: The brightness of this object ensured that it was easily recovered by the analysis software in the red and blue images of all three observations.

Figure B.5: This object was recovered by the analysis software in the red and blue images of each observation. It was also found to have the expected stellar profile.
Figure B.6: Candidate 6 was clearly visible in both the red and blue images of all three observations as a result of good seeing.

Figure B.7: This candidate was successfully detected in the red and blue images of all three observations but appears slightly blurred in the first observation, more likely due to poor seeing than high proper motion.
Figure B.8: The first two observations were taken less than 3.5 hours apart which is close enough that the reference images in the first mosaic contain the position of the object during the second observation, appearing just off centre in both the red and blue reference images. This object was successfully detected in both red and blue images for all three observations.

Figure B.9: Observations 1 and 2 were also taken 2.5 hours apart which is close enough together for the candidate to appear in reference images of the first observation mosaic where they appear to the right of centre. Even with poor seeing in observations 1 and 2, this object was detected in the red and blue images of all three observations.
Figure B.10: This candidate has a magnitude placing at the threshold of detection but was found in both red and blue images of all three observations due to good seeing.

Figure B.11: This object was detected with a magnitude of 20.4 and found to fit a stellar profile in all but the blue image of the third observation where it was too faint to pass through analysis as a viable detection.
Figure B.12: The object was detected in both the red and blue image of the observations. However, in the second observation has poor seeing causing the object to appear blurred while in the 3rd observation, the object is clearly extended and has a non-stellar profile which suggests that this object has a high proper motion.

Figure B.13: The red and blue images of all three observations the candidate are very faint and extended. The poor seeing during the 2nd observation was the cause of the object in the blue image being missed by the analysis software while the extended shape of this candidate in the third observation suggests that it has a large apparent motion.
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