Trans-Neptunian Objects in the Dark Energy Survey

Colin Scheibner, Advisor: David Gerdes

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When asked “What did you do this summer?” not many students get to say, “I hunted centaurs, found dwarfs, and met Trojans.” Well, this is exactly what I did at the University of Michigan Physics REU. With my advisor Professor David Gerdes, I used data from the Dark Energy Survey (DES) to find distant bodies in our solar system outside the orbit of Neptune, or Trans-Neptunian Objects (TNOs). High eccentricity centaurs, dwarf planets, and Neptune Trojans are just a few of the objects we discovered.

Planet 9 and Trans-Neptunian Objects

Why study TNOs? The short answer is that they encode information about the evolution of our solar system. At present, the “standard” model of our solar system’s evolution is the Nice model, depicted in Figure 1. According to the Nice model, the four giant planets initially formed within 20 AU of the sun and were surrounded by a massive planetesimal disk. The giant planets were precariously locked into stable, resonant orbits. However, due to angular momentum exchange with the planetesimal disk, Jupiter and Saturn’s orbits eventually crossed, sending the solar system into chaos. Neptune migrated outward, scattering 99.9% of the planetesimal disk, leaving behind the vast collection of TNOs known as the Kuiper Belt [1].

The distribution of orbits of TNOs in Kuiper belt tells the story of previous events in our solar system. In Figure 2, the orbits of the ~1,300 known TNOs are plotted with the semi-major axis on the horizontal axis and eccentricity on

Figure 1: The Nice Model of Solar Evolution
the vertical axis (the red stars represent TNOs that have been discovered by DES). The majority of TNOs reside in the “classical belt,” which is a collection of low eccentricity objects roughly between 42 AU and 48 AU. The objects are far enough away from Neptune, which has an approximately circular orbit at 30 AU, that they can remain in stable, low eccentricity orbits. These objects are called “cold” because of the lack of dynamic excitation. Accounting for the sharp cut off around 48 AU is one of the achievements of the Nice model [2]. There are TNOs with semi-major axes less than 42 AU whose orbits are stable. These objects avoid scattering interactions with Neptune on mega-year time scales by having orbital periods that are locked in integer resonances with Neptune; even though their orbits physically cross Neptune’s, the TNOs never have close encounters with Neptune due to the resonant timing of their periods. For example, the Neptune Trojans at 30 AU are in a 1:1 resonance, oscillating about the Lagrange points of Neptune. Pluto is a member of the 2:3 resonance at 40 AU. Other members of this group are known as “plutinos,” and those in the 1:2 resonance are quite appropriately dubbed “twotinos.” The relative population of the resonances constrains the timescales on which Neptune migrated outward [2]. Lastly, there are scattering objects, or “hot” TNOs, at higher eccentricities. A line of constant perihelion at 40 AU is plotted in the figure. The sharp cut-off in perihelion indicates that these high eccentricity objects were launched into their high eccentricity orbits by scattering interactions with Neptune, which supports with the Nice model’s hypothesis that Kuiper Belt formed via scattering interactions with Neptune. The populations of resonant, classical, and scattering objects have origins that can be accounted for by working within the Nice model.

Despite the success of the Nice model, several mysteries still remain. In 2003, dwarf planet Sedna shocked scientists because its high semi-major axis and high eccentricity orbit should be the result of a scattering interaction with Neptune, yet its perihelion distance is too large to make gravitational contact with Neptune. Later, later 2012 VP 113, or “Biden” joined Sedna in the class of “detached” objects. It’s as if Biden and Sedna were not pushed out to their

Figure 2: The Distribution of Known TNOs.
orbits, but rather pulled. It gets weirder. In a 2016 paper, Konstantin Batygin and Mike Brown noted that all TNOs with perihelion greater than 30 AU and semi-major axis greater than 250 AU (dubbed “Konstantinos”), have orbits which are physically clustered in argument of perihelion (aop) and longitude of ascending node (lan). After accounting for observational biases, Batygin and Brown argue that there is only a $0.007\%$ probability of this observation occurring by chance [3].

This phenomenon led Batygin and Brown to propose the existence of a ninth planet. As shown in Figure 3, Planet Nine (P9) would have mass $M \sim 10 M_\oplus$, eccentricity $e \sim 0.6$, and semi-major axis $a$ between 300 and 900 AU. The theory makes three key predictions: all TNOs with semi-major axes greater than 250 AU should be anti-aligned with the orbit of P9; there should be a population of TNOs with semi-major axes greater than 100 AU aligned with P9; and there should exist a sizable population of highly inclined, even retrograde, centaurs cutting perpendicularly through the orbits of the known giant planets. The first observation certainly holds for the six known “Konstantinos” and a small population of highly inclined centaurs has been detected. In addition, the P9 hypothesis provides a mechanism for placing Sedna and 2012 VP 113 in their peculiar orbits[3]. Shy of directly detecting P9, finding more distant TNOs will inform our understanding of the evolution of our solar system and either reinforce or disfavor the P9 hypotheses.

Our Research: TNOs in the Dark Energy Survey

The Dark Energy Survey (DES) provides an extraordinary data set for finding distant TNOs. The survey footprint, shown in Figure 4, covers 5,000 $\text{deg}^2$ of the southern hemisphere, or about 1/8 of the entire sky. DES uses the the Dark Energy Camera (DECam) mounted on the 4-meter Blanco Telescope at the Cerro Tololo Inter-American Observatory in Chile. which is sensitive enough to
detect 24 magnitude objects, which are about 1 million times fainter than stars seen with the naked eye. The 5 year project actually contains two survey: the Supernova survey and the Wide-Area survey. The Supernova survey covers 27 deg$^2$, shown in green on Figure 4 and is imaged in each of the 5 bands (g, r, i, z, and y) every 6 days. The Wide-Area survey images the entire 5,000 deg$^2$ footprint with the goal that by the end of the 5 year survey, each portion of sky will have at least 10 observations.

Although the primary scientific goal of DES is to image distant galaxies and supernovae in order to study dark energy, the magnitude depth, temporal coverage, and footprint size make DES a promising place to find TNOs. Most previous TNO survey only search within a few degrees of the ecliptic plane and consequently tend to over-detect classical belt TNOs which spend the majority of their time near the ecliptic due to their low inclination, “cold” orbits. However, the DES survey spans an ecliptic latitude range of $\sim 5^\circ$ to $-70^\circ$, making it well posed to study highly inclined populations of TNOs. Furthermore, DES reaches a full magnitude deeper than most previous TNO surveys. University of Michigan REU students 2 years ago began the search for TNOs in the Supernova survey, finding over 30 new TNOs and increasing the number of known highly-inclined TNOs by 10%. However, the supernova fields represent less than 1% of the total survey area. This summer, we developed a data analysis pipeline to move the search into the Wide-Area survey.

Although examining the Wide-Area survey is more technically challenging due to its sparse temporal cadence, P9 provides a particular impetus for conducting the TNO search. As shown in Figure 4, the hypothesized orbit of P9 intersects the DES footprint. Although there are specific constraints on the mass and orbit of P9, the current location of P9 within its orbit is not a priori known. The Cassini satellite is able to precisely measure the distance between Earth and Saturn. However, the measured distance contains significant residuals when compared to the distances predicted by a detailed post-Newtonian N-body integration. A study was conducted in which the inclusion of P9 at various points in its orbit was shown to either worsen the residuals (shown in red), improve the residuals (shown in green), or have no statistically significant effect (shown in blue) [4]. The favored region resides entirely within the DES footprint. Beyond finding P9, the magnitude depth, footprint size, range in ecliptic latitude, and temporal cadence make DES capable of detecting the distant and highly inclined objects predicted by the P9 theory.

My Project: The TNO Candidate Inspection Tool

Finding TNOs requires a multi-step pipeline. First, we perform difference imaging and machine learning algorithms to identify transient objects in the exposures taken by DECam. Then a linking algorithm is applied to connect transient detections into TNO candidates that are consistent with a Keplerian orbit. Although only three transient detections are mathematically necessary to specify a Keplerian orbit, in order to reduce the number of false candidates, we require that each candidate must have at least four observations that come from at least 3 distinct nights. For a candidate to become a verified TNO, it must undergo a process of visual inspection. The verified candidates are then reported to the Minor Planet Center. This summer I built a candidate inspection tool to
organize and facilitate the inspection and orbit extension of TNO candidates.

The candidate inspection tool takes the form of an online website. Since the analysis is still in progress, I am unable to provide direct pictures of the candidate inspection tool, but I will describe it here briefly. The homepage displays a list of all candidates as well as information about their orbits (semi-major axis, inclination, perihelion, barycentric distance, etc.) and their inspection status (uninspected, accepted, rejected). The name of each candidate links to an individual page for that candidate. The individual candidate page allows the user to adjust flags such as the inspection status or whether or not the candidate has been reported to the Minor Planet Center.

The individual candidate page also displays the orbital elements of the candidate as well as the $\chi^2$ and number of degrees of freedom for the orbital fit. Each candidate is essentially just a list of observation, and so the individual web page lists information about the observations such as date observed, right ascension, declination, band, magnitude, ccd, and other identifying information. Good candidates typically have several observations with relatively consistent magnitudes. The web page then queries a DES image thumbnail generator for 1 arc-minute square cutouts around each of the detections of the candidate. In addition, for each detection image, the website displays images of the same portion of the sky with which the detection image may be compared (the comparison images are ordered by $t_{eff}$, which is a proxy for image quality). The program launches the astronomical application ds9 to draw a circle around each of the detection in order to guide the eye.

Occasionally, the difference imaging and machine learning algorithms overlook detections of the candidates in our database. My program uses the best fit orbit to search all the DES exposures in which the candidate should have appeared. A good way to tell a real candidate from a false candidate is that the real candidates tend to appear in most of its expected exposures. My program draws $1\sigma$ error ellipses around the predicted location of the TNO in each of the expected exposures and provides a table of numerical information for the expected exposures. After the two image arrays (observed and expected), there
are comment boxes for users to leave notes.

I learned several technical skills this summer while building the TNO webpage. The website itself is coded in PHP and uses SQL queries to access a DES database schema that I designed. The candidates are initially stored in csv files. I wrote a python script that loads the csv files into the database, queries online image thumbnail generator, calls ds9 to modify the images, then organizes the image files on a remote machine. I learned how to use git hub and bit bucket to manage the code. The candidate inspection tool is still in development. Moving forward, I plan to improve the aesthetic of the website and implement tools that will expedite the process of adding recovered observations to the list of known exposures.

Cool Results: A (Possible) New Dwarf Planet

This summer was mostly aimed at developing the tools necessary to search for TNOs in the Wide-Area survey. We have over 400 candidates ready to inspect, and the list is still growing! Throughout the summer, we took time to inspect some of the more interesting candidates. Hiding among them, we found a (possible) new dwarf planet.

Two detections of the dwarf planet, taken 2 nights apart are shown in Figure 5. Although our optical measurements we cannot definitively determine the size of the object, the dwarf planet’s heliocentric distance and absolute magnitude are consistent with those of known dwarf planets, as shown in Figure 6. This is a fascinating object, because it is not only likely very large, but also quite distant. At a current distance 92.5 AU, it is the second most distant object in our solar system! We have 16 DES observations of the object spanning 3 oppositions. Initially, our pipeline had overlook the earliest observations of the object. However, my candidate inspection tool allowed us to recover the earliest observations of the candidate, thereby reducing the uncertainties in the candidate’s ephemeris. With the improved uncertainties, we were able to secure Director’s Discretionary Time on the Atacama Large Millimeter Array (ALMA), to measure its thermal emissions. From this measurement, we will be able to determine the diameter of the dwarf planet and officially name it a dwarf planet. The dwarf planet demonstrates the ability of DES to detect distant, fascinating objects in our solar system.

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Figure 5: Exposures of the dwarf planet separated by 2 nights. The dwarf planet lies at the center of the green circles.

Figure 6: The heliocentric distances and absolute magnitudes of known TNOs. Large blue dots represent known dwarf planets.
References


