Machine Learning to Discover Minor Planets

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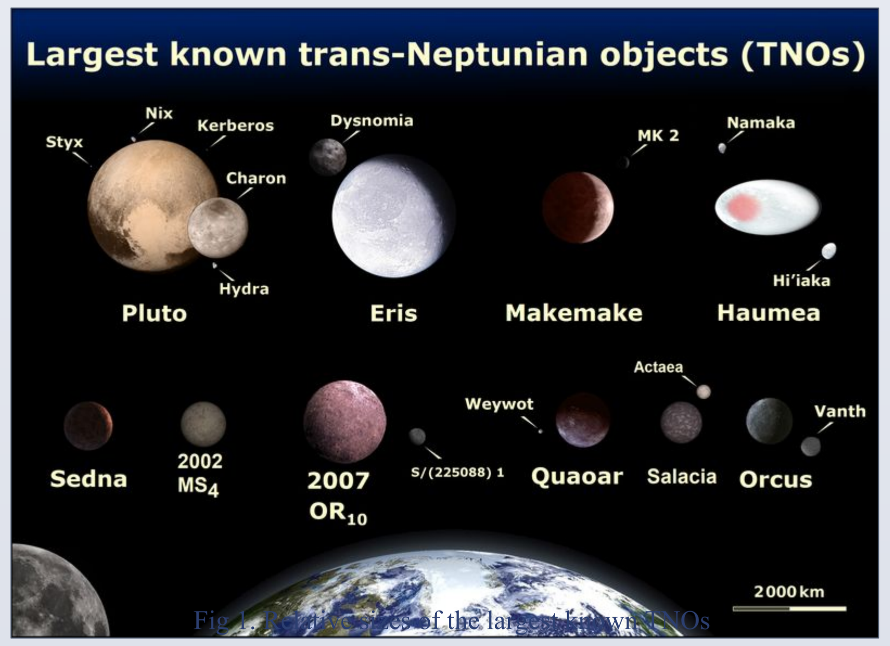
ABSTRACT

The Dark Energy Survey (DES) provides a catalog of transient detections (objects changing in brightness) in addition to a wealth of cosmological data. This research develops machine learning algorithms to discover minor planets outside the orbit of Neptune (Trans-Neptunian Objects or TNOs) from the transient catalogs. These algorithms were tested with specific fields of DES transient data and a new minor planet in our solar system was discovered (2014 VR39). 2014 VR39 is classified as a centaur: a subclass of TNOs that spend part of their orbit inside the orbit of Neptune. It is currently 20.81 AU from the Sun with an estimated diameter of 20-50 km.

WHAT IS A TNO?

Trans-Neptunian Objects (TNOs) are minor planets orbiting the Sun with a semi-major axis greater than that of Neptune. Pluto, the first TNO discovered, was found in 1930; it took researchers 60 years to find another. Today, over 2000 TNOs have been found and we continue discovering more. TNO discovery is an important branch of astronomy and physics that allows us to better understand the dynamics of solar system formation, and may lead to the discovery of hypothesized Planet Nine[1].



DES Transient Data

DES provides a catalog of all objects that appear to be changing in brightness. Discovering forefront TNOs becomes challenging due to the massive amount of noise. Below is a frame of sky where each dot represents a transient detection. The red dots show 3 years of detections of a known TNO orbiting the Sun. The difficulty in discovering new TNOs in a such a densely packed, noise filled dataset is evident.

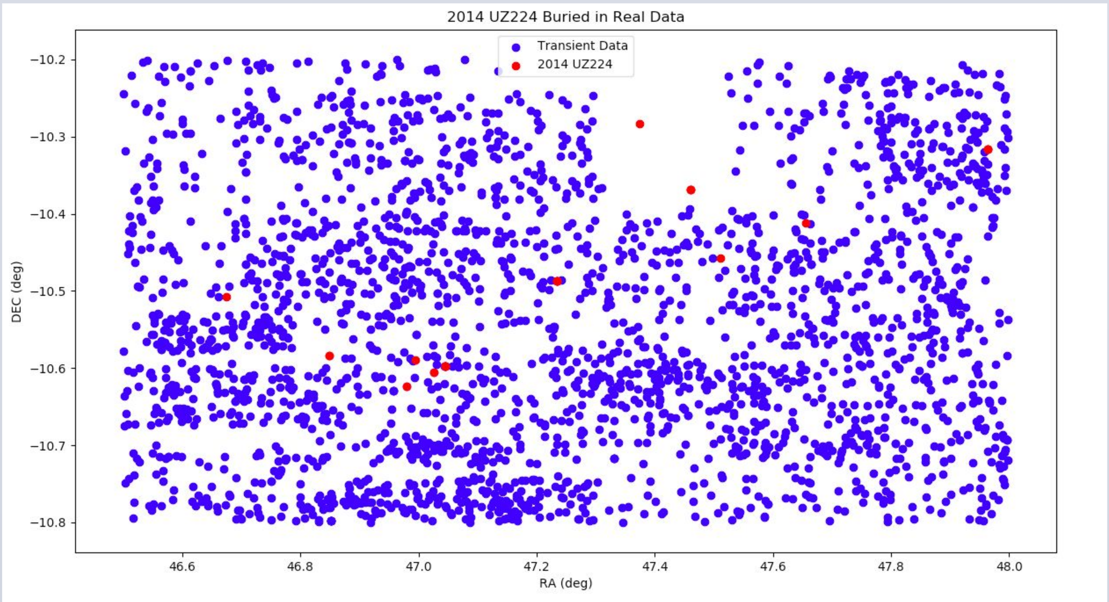


Fig 2. Real DES data with some data omitted for clarity.

Notice if we traced out the orbit of the TNO shown in red it would create a swirled pattern. This is due to the parallactic motion of Earth and adds another layer of difficulty in discovering TNOs from this dataset; especially those with single detections at a given opposition. Now, what if we look at this data as if we were sitting on the surface of the Sun?

SITTING ON THE SURFACE OF THE SUN

Taking away the parallactic motion of Earth allows us to view TNOs from the surface of the Sun (or rather the barycenter of the solar system). From this vantage, they trace linear paths while orbiting at constant velocities relative to their distance. If we look at the data containing UZ224 in a frame de-parallaxed to the correct distance, we can see that its orbit traces a linear path. Analysis of the timestamps attached to each detection would show a constant velocity as well.

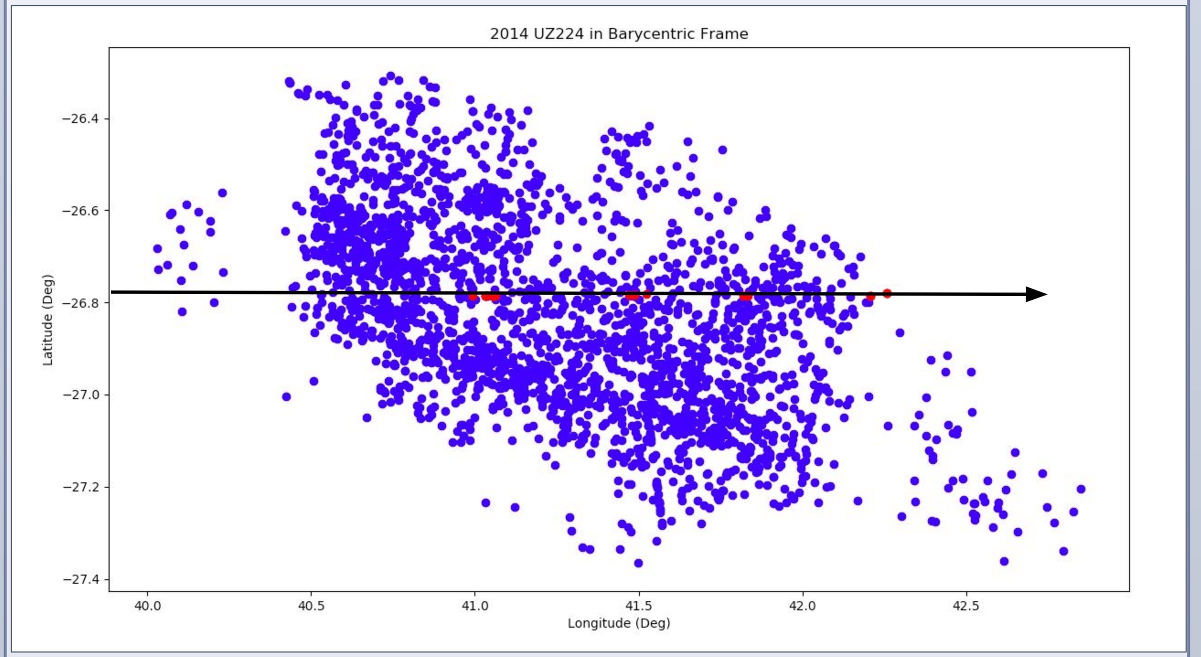


Fig 3. Data in a barycentric frame.

METHODS

After de-parallaxing data to a barycentric frame, a "base" detection is chosen and every possible pair of detections with that base detection is treated as two observations of a real, moving body. A velocity vector is calculated for each pair of detections. Pairs with velocities much greater or much less than the expected value (given the de-parallaxing distance) are thrown away. With classical kinematics we can predicted the location of an object at a given time if we know its current location and velocity.

Discovering TNOs from here is straightforward: if multiple vectors appear to be an object moving at the same speed in the same direction, that will be at the same location at the same time, the detections corresponding to these vectors likely represent observations of a real TNO. By clustering vectors in 5-dimension space (2 dimensions of velocity, 2 dimension of space, 1 dimension of time) we can see these like vectors. If a "base" detection is not an observation of a real TNO, then no clusters will be formed and we move on to another detection. The two free parameters are the initial base detection and the distance for de-parallaxing.

WHAT DOES THIS LOOK LIKE?

The developed algorithm is a Python implementation of the described methods.

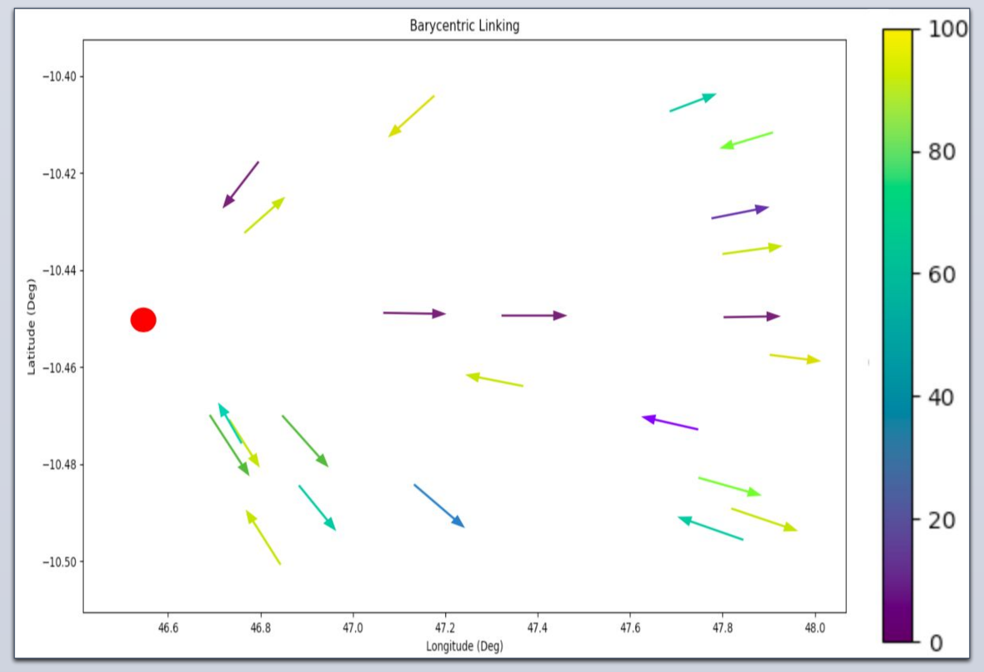


Fig. 4: Base detection as red dot; velocity vectors with other detections represented as arrows. Color shows speeds [arcsec/day]. Many detections removed for clarity.

DENSITY BASED CLUSTERING

We perform density based clustering on these velocity vectors in space and time. Most vectors randomly scatter outwards with unrealistic orbits.

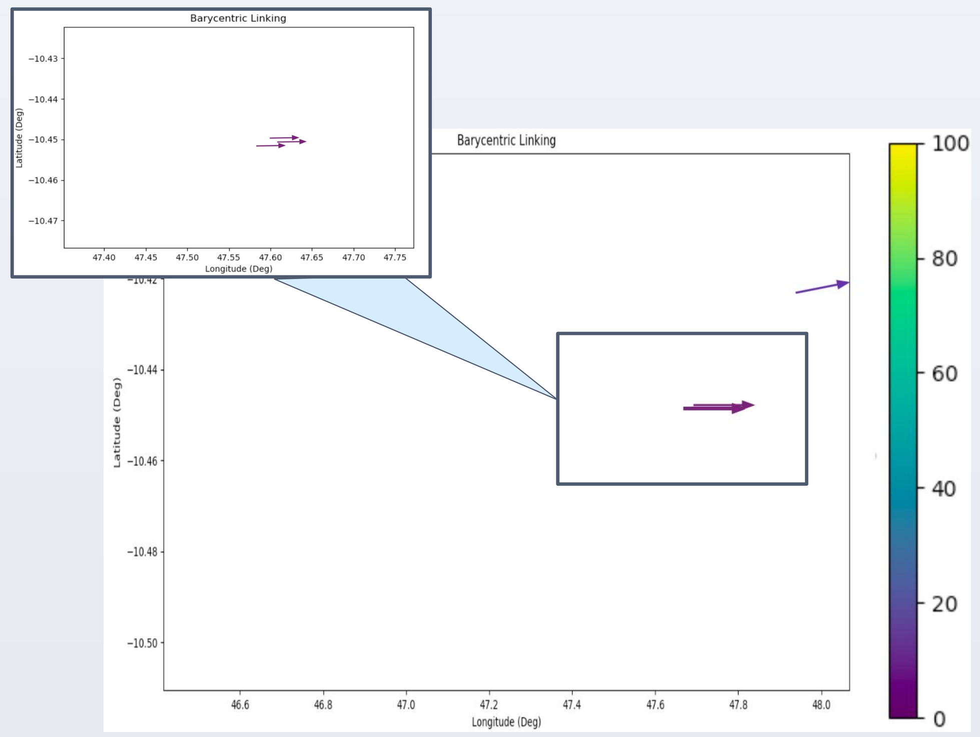


Fig. 5: Most of the vectors have 'flown' offscreen, leaving 3 vectors clustered tightly in our 5 dimensional space. The 4 observations corresponding to these 3 vectors are observations of a real TNO.

RESULTS

The algorithm was applied to DES data in the S field and a new TNO was discovered. 2014 VR39 (named after the year that its first detection was captured by telescopes) is a small body orbiting the sun in the Kuiper Belt.

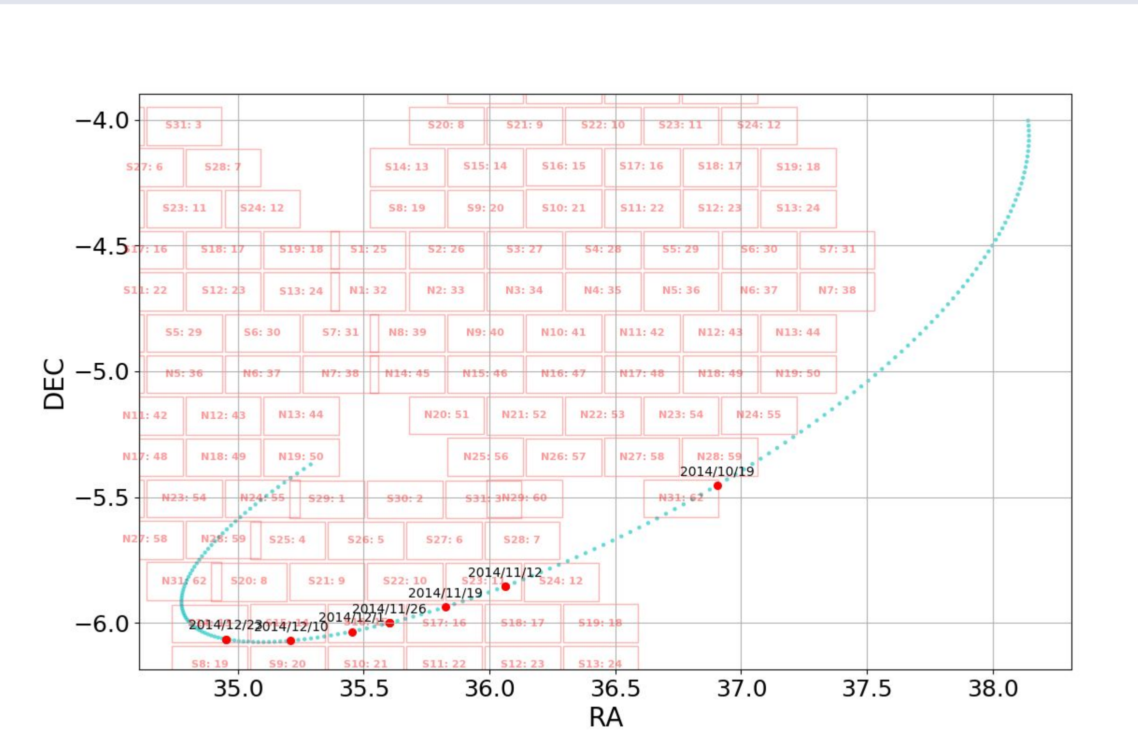


Fig. 6: The orbit of 2014 VR39 and its 7 known detections as viewed from Earth.

ORBITAL PARAMETERS OF 2014VR39

Semi-Major Axis:	27.29135 ± 0.06458 AU
Eccentricity:	0.253530 ± 0.003472
Inclination:	32.753469 ± 0.011651 deg
Current Earth Distance:	20.48 AU
Barycentric Distance:	20.807 ± 0.003 AU
Perihelion:	20.372 ± 0.143 AU
Aphelion:	34.211 ± 0.176 AU
Period:	142.57 ± 0.51 yr
Absolute magnitude:	H = 10.79
Arc length:	64.899 days

PLANET NINE?

New TNOs give valuable information about solar system formation and help us paint a more thorough picture of our solar neighborhood. They may also be the key to unlocking a new secret about our solar system, Planet Nine.

The idea of Planet Nine gained traction following the discovery of Sednoids; TNOs orbiting our Sun with semi-major axis > 150 AU[2]. The irregular orbits of Sednoids cannot be explained through gravitational interactions with the giant gas planets[1]. These orbits might be the result of a close encounter with another star early on in our Sun's birth cluster[3,4]. According to Dr. Mike Brown at Caltech and others, an undiscovered ninth planet in our solar system best explains these orbits. The number of known TNOs at this distance is limited, and a strong statistical prediction of Planet Nine requires many more to be discovered.

Some scientists believe it is likely that Planet Nine has already been observed but undiscovered due to the difficulty in detecting its slow orbit and low brightness in observational data. Improvement in TNO detection algorithms allows us to explore this space as well.

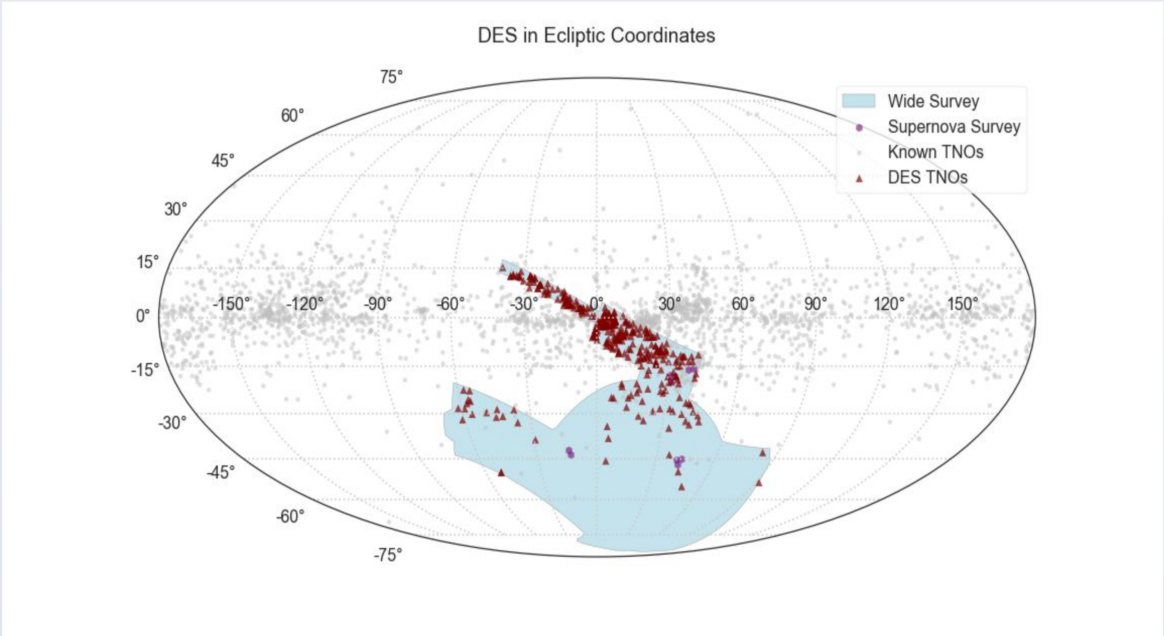


Fig. 6: TNOs recently discovered in Dark Energy Survey data. An undiscovered detection of Planet Nine may be lurking in detections near the ecliptic.

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