Next Steps in studying the Outer Solar System

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Science Frontier Panels:
The Planetary Systems and Star Formation (PSF)

1 Introduction

Over the last 15 years, our viewpoint on planetesimals in our Solar System has changed dramatically. It is now clear that these large populations of planetesimals, from Trans-Neptunian Objects (TNOs) and planetary Trojans to Main-Belt Asteroids (MBAs) and Near Earth Objects (NEOs), can provide important clues to the history and formation of the Solar System, through their physical properties and orbital distributions.

Currently, our understanding of each of these populations is limited by small sample sizes. While over 1,000 TNOs have been discovered, fewer than half of these have well-known orbits or have been discovered in well-characterized surveys where the discovery biases can be understood. Only several hundred TNOs have measured colors, and these are mostly brighter objects. The understanding of MBAs is much further advanced, and illustrates what is possible as the sample size is increased, however the completeness of various planetary Trojan populations is still unknown.

Over the next 10 years, large wide-field, synoptic surveys can enable significant observational advances in our understanding of the solar system by creating large, well-characterized catalogs of these planetesimals. Understanding the orbital distribution, color distribution, detecting collisional families and measuring spin and shape properties of large numbers ($> 20,000$ TNOs, $> 1,000,000$ MBAs) of these small bodies will be possible. These large sample sizes are required to detect rare or unusual populations, as well as provide a sample which is still statistically significant when subdivided amongst different subclasses. Further advances in understanding planetary formation and the evolution of our solar system will result from a comprehensive understanding of these populations.

2 Feasibility

An all-sky survey with a frequent cadence and high photometric accuracy in multiple passbands is necessary to meet the observational requirements for the next step forward in understanding our solar system. To meet the sample size requirements to identify and characterize rare objects on the order of 20,000 TNOs are needed, implying a survey limiting magnitude of about $r = 24 - 25$ per exposure based on current TNO luminosity function measurements [8, 9]. To measure colors accurately enough to detect links or differences between populations, gri magnitudes accurate to about 0.01 magnitudes are required. These requirements cannot be met by current facilities, but can be achieved by future facilities of PanStarrs-4 and LSST .

Being able to correctly link and measure orbits for all objects is strongly dependent on cadence – identifying objects beyond Neptune may only require three observations per night on a series of two nights, two times a year spaced at the right intervals, but simultaneously identifying and linking NEOs requires multiple observations per night, on a much closer spaced time scale. Uncertainty in the ephemeris prediction grows with time, reducing observer's ability to correct link different observations of the same object. By observing the entire visible sky twice in a single night and repeating this process every few days, moving objects across the entire solar system could be linked and highly accurate orbits computed. This fast observing cadence also allows for the discovery of highly unusual orbits which may be otherwise missed due to assumptions required for calculating short observational-arc orbits [19]. Before Gladman *et.al* [12] conducted followup observations of 2000 CR105 for several months immediately after discovery, the existence of objects on 'detached' orbits was unknown — even though it is extremely likely that previous members of this population were discovered but then lost due to large errors in their ephemeris predictions. Similarly, there may be more retrograde TNOs or other unusual objects which have been lost after discovery, due to degeneracies in the orbit computation which can make a few closely spaced observations of a distant retrograde TNO appear to be a nearby, prograde asteroid. Current facilities cannot meet these temporal requirements unless dedicated to solar system observations, but the future facilities of PanSTARRS-4 and LSST meet these requirements for the observational schedule per object over a few months or about seven months of the year (respectively).

This frequent cadence of observations also facilitates the measurement of shape and spin properties of each object, particularly if the data are released to a wider community to allow for additional measurements to fill in portions of the lightcurve necessary for sparse light curve inversion.

A data processing system adequate to identify and link the moving objects, and provide correct orbits for objects throughout the solar system is also required. This is a significant computational challenge, but a “Moving Object Pipeline System” for PanSTARRS is already in advanced stages of development and should be adaptable to future facilities such as LSST.

Finally, a complete understanding of the biases relating to flux limits in each observation, cadence of observations, pointing history and orbit calculations is crucial for interpreting the survey results.

3 Planetary Formation and Solar System Evolution

Understanding how planets formed in our solar system is inextricably related to understanding where they formed and their subsequent orbital evolution. The discovery of large numbers of TNOs in mean-motion resonance with Neptune, together with the discovery of giant extrasolar planets at small distances from their stars, created a new vision of our solar system. Instead of a static place, where the giant planets formed in their current locations, Malhotra [27] proposed that a gradual outward migration in Neptune’s orbit could have gathered TNOs into resonance, trapping them there at a higher density than in the rest of the Kuiper belt. In this new vision of a more dynamic solar system, the large populations of small bodies preserve an invaluable fossil record of the orbital evolution of the giant planets.

In recent years, the Nice model has proposed [34] that all giant planets formed at less than 14 AU from the sun and the solar nebula was truncated near 30 AU. The giant planets and small bodies in the solar system subsequently evolved to their current state through planetary migration due to angular momentum exchange with planetesimals. The Nice model presents an intriguing theory which could account for many previously unexplained problems in various small body populations: the mass depletion observed in the Kuiper belt [25] and the asteroid belt [31], the orbital distribution of Trojans [29], and the late heavy bombardment [15]. However, competing theories such as a slow planetary migration [17] or a rogue planetary embryo passing through the outer solar system [11] could also explain some of these features. Each model has its strengths and weaknesses. While the Nice model has been applied to a wider variety small body populations from asteroids to Trojans to TNOs, it still has trouble explaining the detached KBOs with perihelion beyond 50 AU as well as the orbital distribution of the cold classical Kuiper belt. On the other hand, stellar flyby, planetary embryo, and slow planetary migration models have problems recreating the inclination distribution of the hot classical Kuiper belt and cannot explain the orders of magnitude of mass depletion required to create the size distribution observed in the present-day Kuiper belt.

A clear picture of the orbital distribution of small bodies throughout the entire solar system would provide the means to test each of these models and provide constraints for further model development. In particular, these orbital distributions need to be accompanied by a clear understanding of the selection biases present in the observed distributions.

Combining the orbits with color information accurate to 0.01 magnitudes for a significant fraction of the planetesimal allows for additional valuable explorations of subpopulations and similarities between different groups. For example, differences between the 'hot' and 'cold' classical Kuiper belt are evident by looking at the statistical distribution of inclinations of classical belt objects. However, the color [6, 8] differences between the two groups are clear, indicating a strong likelihood of significantly different dynamical histories, rather than just a bimodal distribution of inclinations (see Figure 1). These differences are hard to explain in any of the current models of the outer solar system, thus providing another important avenue for testing these models of the evolution of the solar system. As another example of the application of color data to understanding the history of small bodies, giant planet irregular satellites with a variety of inclinations show clear 'families' when their orbital parameters are combined with color information [16](see Figure 2). With the addition of this information, the likelihood of different methods of capture mechanisms — gas drag capture of a series of small bodies versus capture of one parent body which was then broken apart through tidal stresses or collisions — can be evaluated.

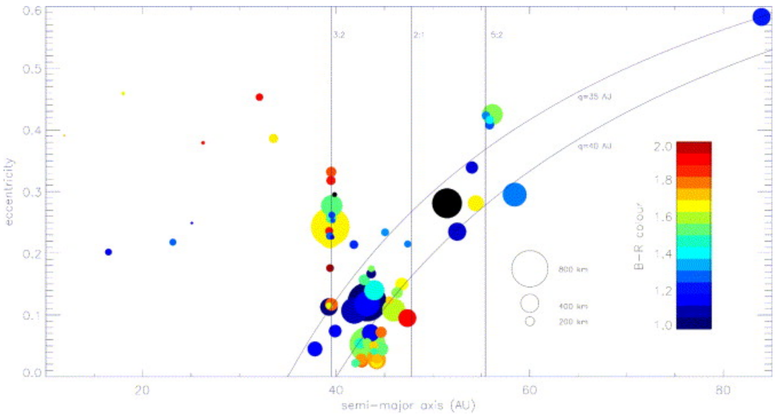

Figure 1: Figure from [7], indicating the color of TNOs and Centaurs in the orbital eccentricity versus semi-major axis plane, sizes of symbols are proportional to each object's diameter. The color of each object is coded to the measured color. Very red objects are coded in black. Note that the 'cold classical belt' ($e < 0.2$, 42 AU$< a < 48$ AU) contains only red objects: objects throughout the rest of the orbital phase space are a variety of colors. This difference in color for cold classical belt objects could indicate a different dynamical history for these objects, compared to the rest of the TNOs.

4 Rare and Unusual Populations

The discovery of Sedna on an eccentric orbit with perihelia 76 AU and semi-major axis 495 AU [4] — an orbit entirely contained beyond the outer edge of the classical Kuiper belt (≈ 50 AU) and inside the inner edge of the Oort cloud (≈ 2000 AU) — provides important clues to the galactic environment of the early solar system. This orbit cannot be explained through interaction with any known solar

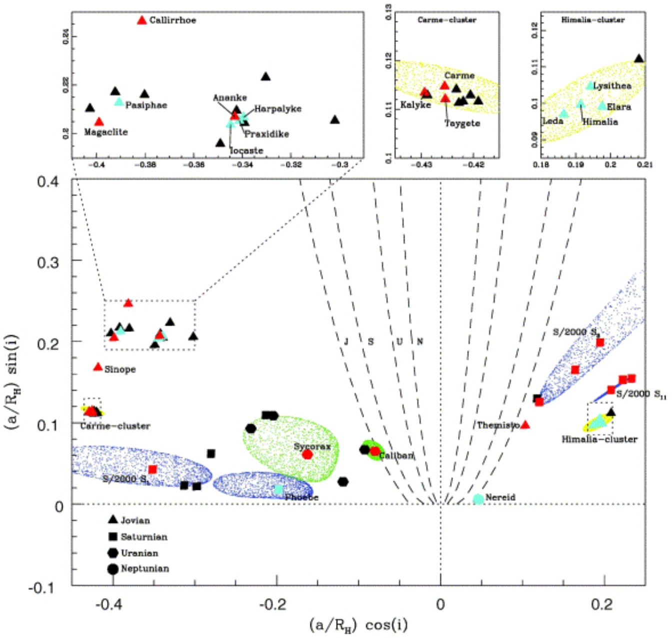

Figure 2: Figure from [16], showing the mean-motion semi-major axis and inclination of the irregular satellites for each giant planet, normalized by the Hill-sphere radius of the satellite's parent planet. Irregular satellites with measured colors have been binned into 'grey' or 'red' color bins and are plotted according to blue for 'grey' objects and red for 'red'. The colored ellipses indicate the area of $a - i$ space where each cluster could disperse, given a catastrophic fragmentation event.

system object, but appears likely to be the result of interaction with a passing star early in the history of the solar system [23, 28].

There are a handful of other TNOs, called 'detached' TNOs [13], which may also be the result of similar interactions. These include 2000 CR105 [12] and 2004 XR190 [1], which also have perihelia beyond 45 AU. All of the detached TNO orbits are hard to explain because each one shows signatures of some dynamical perturbation in the past (a high eccentricity or inclination), yet there is no clear indication of what that perturber could have been. Because their perihelia are beyond the gravitational influence of the giant planets, these orbits could not have been perturbed by any currently known member of the solar system. It is possible that a rogue planetary embryo, embedded in the outer solar system for some time, could have perturbed some of the objects, but this seems unlikely in the case of Sedna or 2000 CR105 due to their exceedingly large perihelia. In addition, with the small sample size of these unusual objects, it is difficult to know what may be explained as the unlikely outlier of a distribution, what can be explained as the 'first discovery of its kind' due to observational selection biases in flux, inclination and observational followup [21] or miscalculated orbits [19], or what must be explained through a new model of the outer solar system.

Some models of stellar flybys also predict the existence of retrograde TNOs, which can be created if planetesimals from the passing star are captured into our solar system [23] or by perturbing solar system planetesimals out of our Oort Cloud through a nearby passage, especially if the young solar nebula environment was a dense cluster [2, 20]. One retrograde TNO, 2008 KV42 with inclination of 102°, has recently been discovered with the CFHT in a high-ecliptic latitude TNO survey being conducted by Gladman *et. al.* as an extension of the CFEPS wide field survey [18, 22].

The major problem with rare populations such as Sedna-like objects or retrograde TNOs is that a handful of objects is not a good statistical sample. A few hundred would be desirable, but because they compose at most a few percent of the observed population of outer solar system objects, this indicates the need for a total sample size of $> 20,000$ TNOs. By studying these rare populations, we gain valuable insights into processes in the history of the early solar system, especially how the early solar system was interacting with the local galactic environment.

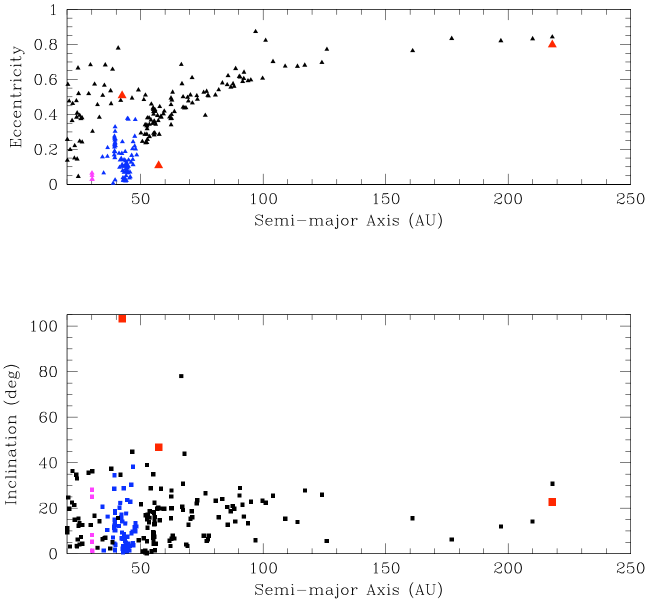

Figure 3: The orbital element distribution of the classical Kuiper belt objects (blue), the Neptune Trojans (red), and the Centaurs/Scattered Disk Objects (black), as tabulated and calculated by the Minor Planet Center. Some members of rare dynamical classes (2000 CR105, 2004 XR190, 2008 KV42) are shown in red.

5 Early Solar System Environment

The early environment within the solar system can be probed by studying the properties of collisional families, the binary fraction of small bodies, and their physical properties of shape and rotation rate. While the study of the populations of the outer solar system makes use of their presence as vast numbers of test particles sampling the gravitational history of the giant planets and other perturbers, significant additional insight can be gained by realizing that these test particles also interact. Collisions and close encounters in the early solar system result in families of shattered objects, captured and collisionally-induced satellites, rapid rotations.

To date, only one collisional family of objects is known the in outer solar system. Haumea, the fourth largest object known, orbits within a dynamical cloud of debris left over from a giant impact with a comparably-sized object [3]. Such a giant impact is exceedingly improbable in the current environment, and even difficult to explain in a more dense earlier environment. Levison *et. al.* (2008) [26] realized that collisions between objects being scattered by Neptune could potentially explain this

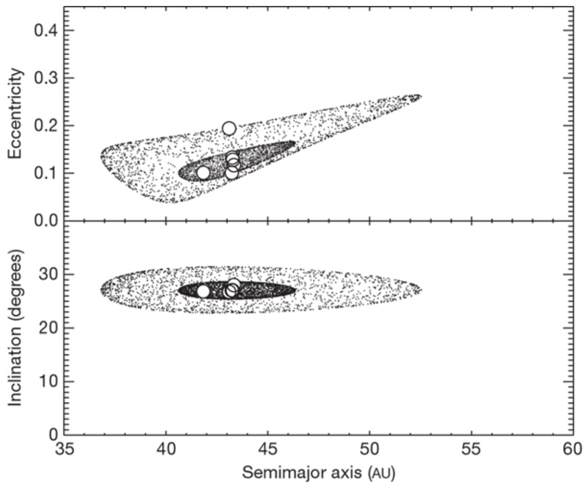

Figure 4: Figure from [3]. The open circles give the proper orbital elements of the fragments, as of 2007. The widely dispersed small dots show the orbital elements possible from a collision centered on the average position of the fragments and with a dispersive velocity of 400 m/s. The more tightly concentrated dots show orbital elements expected if the collision had a dispersive velocity of 140 m/s. The orbital dispersion from these collisions indicates that identifying collisional families in the Kuiper belt will require accurate orbital elements for a large number of objects and may be strongly aided by color or other physical measurements.

family. This suggests that many collisional families should exist in the outer solar system and their orbital distributions could trace the scattering history of the early Kuiper belt.

The Haumea family was recognized only because each of its members shares the same distinct infrared spectrum: a surface dominated by almost pure water ice. Without the spectra, the family could not have been recognized as no statistically significant concentration could be identified by dynamics alone. See Figure 4. The icy surface of the family members is likely the result of the differentiation of proto-Haumea before impact, where the family members are pieces of the pure ice mantle. Other collisional families in the Kuiper belt will likely not be identifiable by their spectra, but rather will have to be identified as significant concentrations in dynamical space, as the asteroid families are identified. Such identification will only be possible when large-scale surveys find significant numbers of objects in a statistically understandable manner and will be aided by information on colors and perhaps other physical properties.

Satellites are another consequence of interactions in the outer solar system. In the early more-dense environment satellites can be captured by the effects of dynamical friction [14], through two-body collisions or exchange reactions in the presence of a third planetesimal [10, 35]; large Kuiper belt objects appear to have tiny satellites formed in giant impacts [5]. Each of these processes traces the different environments of the regions where the objects formed. Work with HST has shown that the cold classical Kuiper belt has a significantly higher fraction of captured satellites than any other TNO population [30]. With the small number of observations of other sub-populations, however, no good statistics are available to examine satellite fractions. A large-scale survey which finds many objects will also find many satellites ($\approx 50 - 100$) separated by arcseconds, allowing detailed study of these systems.

Rotations are an obvious consequence of the accretion and collision process. To date, even after painstaking work, little is known about rotations of objects in the outer solar system [33]. To measure a rotation, each object must be individually tracked and monitored with a large telescope for hours or days. Some rotations show up easily on these time scales, some are heavily aliased or too subtle for detection. Our current understanding of rotations is so heavily biased by these factors that it is difficult to make any comprehensive interpretations.

Nonetheless, a few interesting objects stand out. The large objects Varuna and Haumea have extremely rapid rotations (6 hrs and 4 hrs, respectively), which cause them to elongate into triaxial ellipsoids [24]. Haumea is known to have suffered a family-producing collision, which likely imparted the spin. No such family has yet been dynamically linked to Varuna. Observations of rotations have suggested, with poor statistics, that a large fraction of objects could be contact binaries [32]. Such contact binaries could be a natural consequence of the dynamical-friction induced capture in the early solar system [14] if the dense-early environment persisted for long periods of time, allowing orbits of captured satellites to decay.

A multi-color survey with frequent time sampling and relative photometric accuracy better than 0.005 magnitudes would allow measurement of lightcurves for thousands of TNOs, yielding rotation periods, phase curves, thus allowing conclusions about shape and spin properties and providing clues on the early environment in the outer solar system.

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