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Probing The Solar System's Outermost Frontier: The Future of Kuiper Belt Studies

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Abstract. Priorities are described for research on trans-Neptunian Objects (TNOs), a recently-discovered (thereby excluding Pluto and Charon) population of small, outer solar system objects with important implications for the early history of the solar system. We conclude that we must discover and obtain accurate orbits for an unbiased sample of ~5000 TNOs over the next decade and a significant fraction of these objects must be targeted for more detailed physical observations. A broad range of complementary theoretical and laboratory studies are also needed, and we must work towards direct spacecraft exploration of TNOs as soon as possible.

EXECUTIVE SUMMARY

Since the discovery of the first trans-Neptunian object (TNO) in 1992, the trans-Neptunian region has surprised researchers time and time again. For example, many TNOs have been found in mean motion resonances with Neptune while others are in highly inclined and/or eccentric orbits (eccentricities as large as 0.9). Colors of TNOs span a remarkably wide range (B−V from 0.5 to 1.3), and 6 objects are now known to be binaries. Unexpected properties such as these have led to a re-evaluation of the history of the solar system.

The trans-Neptunian region represents the best known source for the study of the formation and evolution of the outer solar system because TNOs are relatively unaltered remnants from that early epoch. The orbital element distribution of TNOs is expected to bear scars from the late stages of the formation of Uranus and Neptune. By understanding this population, we can obtain information about the masses and locations of planets during earlier times, as well as external influences which could have impacted the solar system. Similar arguments apply to physical studies of TNOs, since their small sizes and low temperatures should have prevented their bulk chemistry from substantially changing since their formation. The TNOs thus far discovered have supplied us with tantalizing clues about these issues. However, a complete understanding of this important region cannot be achieved without considerably more effort.

The observational challenges presented by TNOs are immense, owing to their extreme distance and faintness. A balanced approach involving observations, spacecraft exploration, and Earth-based investigations is needed to maximize our understanding of the trans-Neptunian population and to realize the greatest scientific benefit from its study. This panel recommends a research program including these components:

- Obtaining a large, unbiased sample of some 5000 TNOs with accurately determined orbits is a top priority. To achieve this goal will require carefully coordinated search and recovery efforts for well over 100 dark nights per year for a decade on 4 m class telescopes.

- A diverse array of observations is needed to measure physical properties of as many TNOs as possible, and deep surveys are needed to probe fainter and more distant objects. These observational projects will require access to state-of-the-art ground-based, airborne, and space-based observatories.

- Close up, direct exploration of a few TNOs and in-situ measurements of their environment are needed. These tasks can only be accomplished by spacecraft. Prompt development and launch of NASA's Pluto Kuiper-Belt (PKB) mission is an essential first step.

- A wide variety of theoretical and laboratory studies are urgently needed to enable us to properly interpret observational data from each of the above efforts.

These components complement one another in important ways. If any part of this balanced program is neglected at the expense of another, overall progress toward understanding the outer solar system will be significantly retarded.

This panel believes that a top priority of the community is obtaining an observationally unbiased sample of approximately 5000 TNOs brighter than ~24^{th} mag, as well as a smaller sample of fainter objects. The orbits of this sample must be determined to sufficient precision that we can (*i*) discern the dynamical fine-structure of the belt and (*ii*) recover these objects for physical studies. To achieve these goals, we must discover new objects at rates exceeding current discovery rates, coupled with a greatly-expanded campaign of astrometric follow-up. The need for consistent recoveries cannot be emphasized strongly enough. Five years ago, a primary impediment was the paucity of known objects. Now, the major stumbling block is lack of dedicated recovery efforts. Recovery failures have produced a sample that is burdened with complicated and unknown biases. It would be far more scientifically valuable to have a thousand TNOs with well-determined orbits and minimal observational biases than to have ten thousand with poorly determined orbits and/or subject to unknown observational biases.

To cost-effectively obtain a suitable sample of TNOs will require both deep and wide surveys. The primary effort of accumulating 5000 good orbits can be accomplished with wide-field surveys carried out at telescopes in the 4 m aperture class. Two dedicated 4 m telescopes could do an excellent job of discovering and following this sample over the coming decade. Deep surveys at larger telescopes are also needed, for studies of the spatial and size distributions of fainter objects.

In addition to search and recovery efforts, a great variety of complementary observational studies are needed to determine rotation rates, radii, albedos, colors, masses, and compositions of a significant and minimally-biased sample of the known TNOs, enabling us to draw conclusions about the ensemble properties of distinct sub-populations. These observations require access to state-of-the-art astronomical facilities including HST, Keck, and eventually SIRTF, ALMA, and NGST, as well as possible future facilities such as LSST or SNAP. Additionally, Kuiper belt research needs must influence the design of future instrumentation for these observatories.

The community places a high priority on direct spacecraft exploration of a few objects. Close flyby investigations offer unique opportunities to apply the tools of planetary geology to learn about the surfaces and interiors of TNOs. Spacecraft are also the only way to obtain in-situ measurements of the trans-Neptunian environment which are essential to understanding the evolution of TNO surfaces.

All of these investigations must be supported by theoretical research. Comprehensive numerical studies of the formation and the dynamical and collisional evolution of the outer solar system are needed to interpret the observed distributions of the thousands of objects to be discovered in the trans-Neptunian region. Studies of the radiative transfer and thermal and compositional evolution of TNO surfaces and interiors are also essential to interpreting observational data.

Laboratory studies are required for interpreting diverse types of observational data and to provide inputs to theoretical and numerical models. Studies of optical constants, photolytic and radiolytic pathways, low temperature chemistry, gas-solid interactions, and thermal and mechanical properties of outer solar system materials are all urgently needed.

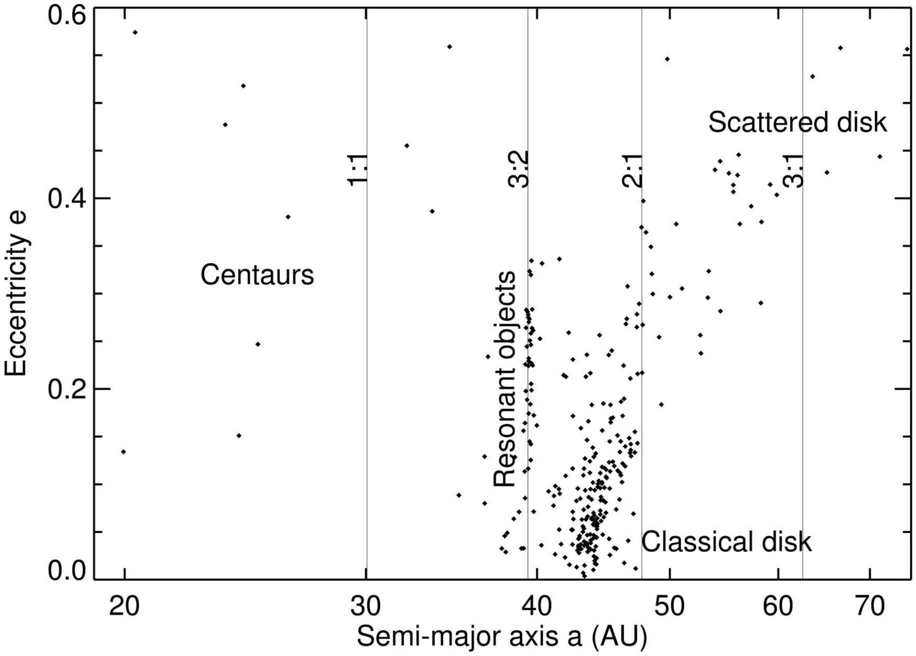

Figure 1. A still-incomplete picture of the dynamical structure of the Kuiper belt begins to emerge when objects with well-known orbits are shown on a plot of semi-major axis versus eccentricity. Mean motion resonances with Neptune's orbit are indicated by vertical lines and major dynamical classes are labeled.

REPORT

1. Current State of Knowledge

Since the discovery of the first trans-Neptunian object in 1992, there has been an explosion of activity directed towards learning about the contents of this fascinating part of our solar system. A decade later, we have discovered hundreds of objects, but our ignorance remains profound about many of their most basic characteristics (Figure 1). While we have determined the visual-wavelength colors and lightcurves for a small subset of the known TNOs, we know almost nothing about the sizes, shapes, compositions, and geology of the population as a whole. Infrared spectroscopy of a few TNOs points to a remarkable diversity of surface compositions, but a taxonomy of TNOs does not yet exist. We have found that the dynamical structure of this region is surprisingly rich, with some objects in Neptune mean motion resonances, others in near-circular orbits (classical Kuiper belt objects, or KBOs), and still others in highly inclined and eccentric orbits (Scattered Disk objects, or SDOs). The origin of this diversity remains mysterious. We do not even know how far away from the sun the trans-

Neptunian population extends, and have probably not yet discovered many of its largest members.

The potential value of the trans-Neptunian region as a source of information about the formation of the outer solar system is immense and thus our current state of ignorance is especially troubling. The orbital distribution of TNOs bears scars from the late stages of the formation of Uranus and Neptune and is indicative of a very violent past. We need to understand, in detail, the structure of this distribution in order to obtain vital clues to the masses and locations of planets at early times in the solar system. We may also be able to glean information about the Sun's stellar nursery and/or the more recent interstellar environment by studying these structures.

Furthermore, TNOs are believed to be among the most pristine objects in the solar system, with interior compositions little changed since the time of their accretion in the outer parts of the protoplanetary nebula. By studying TNO compositions along with the processes which have acted on their surfaces and interiors over the age of the solar system, we can gain a potentially unique window into the chemical evolution of the protoplanetary nebula and the source material from which our solar system formed.

So little is known about the Kuiper belt that it will be essential to attack our key scientific questions from many different directions simultaneously, if we are to make significant progress during the coming decade. The remainder of this paper will catalog our key scientific questions and then will describe a number of complementary investigations which this panel believes must all be pursued to achieve the kind of balanced approach that is needed.

2. Key Science Questions

As emphasized above, very little is known about the trans-Neptunian region and the objects which occupy it. Over the next decade we need to address the following four key science questions:

- What is the dynamical structure of the Kuiper belt and what processes sculpted it?
- What different classes of TNOs exist, and what is their origin?
- What are the compositions and structures of TNO interiors and surfaces and what processes act on them?
- What does the Kuiper belt tell us about formation of the solar system?

To effectively tackle these very broad and general questions, they can be broken into smaller, more readily addressable questions such as:

- How did TNO orbits get so dynamically excited and is there a dynamically cold population?
- What is the radial distribution of TNOs, and is the apparently sharp edge of the classical belt real? (if so, what caused it?)

- What are the compositions of TNO surfaces?
- How does composition relate to color and albedo, and what is the reason for the observed diversity of colors?
- What is the overall size-frequency distribution of the trans-Neptunian population, and what are the size distributions of different classes of TNOs?
- What relationships exist between dynamical and physical classes of TNOs?
- Are apparent correlations between absolute magnitude, inclination, and color in the main belt real, and what do they mean?
- What other large objects remain to be discovered? Are there more Plutos and Charons?
- What are the inclination distributions of TNO sub-populations and what caused them?
- What changes occurred in TNOs during and soon-after accretion?
- What does the distribution of TNO rotation periods look like?
- Where is the transition from irregular to spherical shapes, and what does this tell us about TNO interiors?
- Which TNOs have satellites, and how do they differ from moon-less TNOs?
- How do TNOs get into orbits like that of 2000 CR_{105}, with huge eccentricities and perihelia well beyond Neptune's?
- What caused the resonant structure of the Kuiper belt and how did it form?
- What are the connections between TNOs, centaurs, trojans, comets, and icy satellites, and how are their dynamical histories and compositions related?
- What can we learn about TNOs by extrapolation from comet and centaur studies?
- How does our Kuiper belt compare with disks around other stars?

It is readily apparent that a huge number of questions awaits our pursuit.

3. Recommendations

During the coming decade, this panel recommends:

- A pair of dedicated 4 m class telescopes (or their equivalent in dedicated dark time) be made available for wide-field search and recovery efforts.

- A LARGE amount of time be made available on various very large (6 to 10+ m and space-based) telescopes with adequate instrumentation for physical studies and deep surveys.
- NASA's "Pluto-Kuiper Belt" (PKB) mission, the only means of of doing crucial in-situ measurements of TNOs, proceed expeditiously to launch.
- A vigorous program of complementary laboratory, theoretical, and numerical investigations be supported.

A balanced approach will be essential to maximize our scientific understanding of the trans-Neptunian population. Indispensable research components include discovery of a large, unbiased sample of ~5000 TNOs with adequate astrometric follow-up, deep surveys to establish bounds on the Kuiper belt, observational efforts to determine TNO physical properties, in-situ spacecraft investigations of TNOs and their environment, and a wide variety of theoretical and laboratory studies. In the remainder of this section, we describe specific investigations which must be part of a balanced program to advance understanding of this important region of the solar system. Each component of this balanced program depends on progress in the others. If one area is neglected at the expense of another, overall scientific progress will suffer.

3.1. TNO recoveries and determination of orbital elements

The discovery rate of TNOs has dramatically increased over the last few years, making the need for a dedicated recovery program particularly urgent. 146 TNOs were discovered in 1999, more than in all previous years combined. 169 were discovered in 2000, and the rate of discovery continues to increase. Relative to discovery, it typically requires 5 times more telescope time for recovery efforts in order to sufficiently refine the orbital elements of a new TNO. This factor arises because recoveries must be made at least once during the year of discovery and each of the following 2 to 3 years (oppositions). As of mid-November 2001, ~540 TNOs have been discovered, but more than half of them have had no second-opposition recovery observations, and about half of those have had no measurements for more than a year (Figure 2); nearly 20% of all objects are irrecoverably lost and another ~10% are in immanent danger of being lost. This distressing record shows that current programs are not sufficiently following up their discovery observations.

In general, discovering objects only to lose them is of little use and wastes resources. Objects must be observed frequently enough that their orbits can be accurately determined. Accurate orbital elements are essential to ensure objects will be recoverable for physical observations. To provide useful constraints on dynamical models, it is necessary but not sufficient to acquire a large catalog of well-observed TNOs. It is even more important to avoid, or at least understand quantitatively, observational biases which favor recovering objects in particular types of orbits. Ephemerides used by observers for first recoveries are based on educated guesses, which in turn are based on the current understanding of Kuiper belt orbits. If an object is found at a heliocentric distance less than 40 AU, it is typically assumed to be in the 2:3 mean motion resonance with Neptune. If it is found beyond 40 AU, it is often assumed to be in a circular

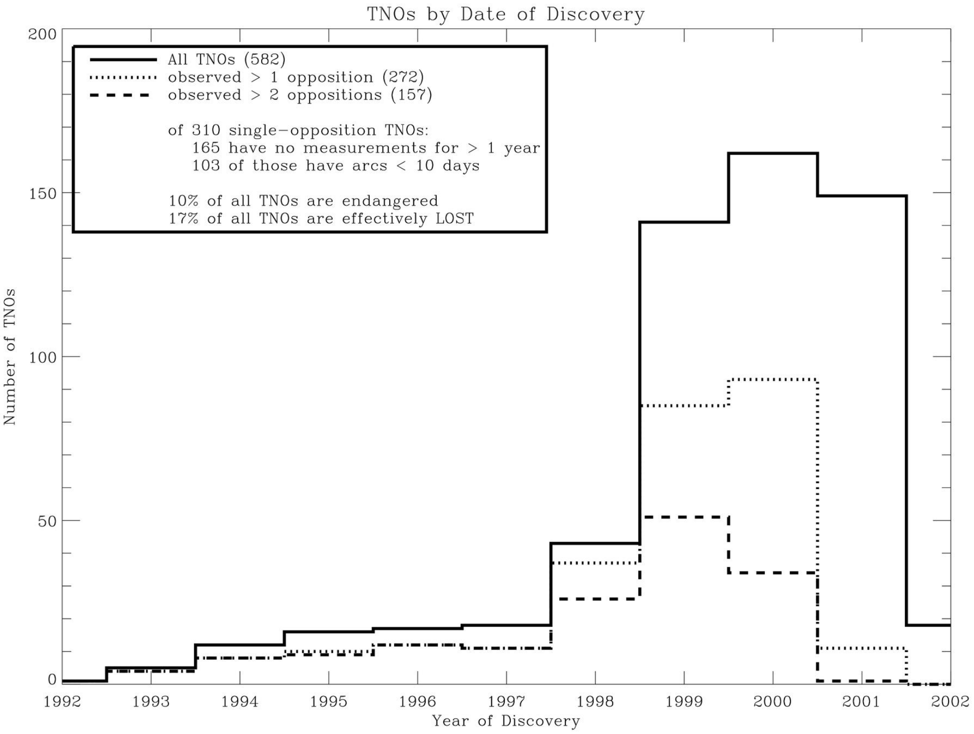

Figure 2. Discovery and recovery statistics (as of March 2002) of the currently known TNOs. Note that the recovery rate has significantly fallen behind the discovery rate (solid line) over the last several years. Without dedicated recovery efforts, the sample of objects in well-determined orbits will become increasing biased as the fraction of lost objects grows.

orbit. After enough time has passed since discovery, only those objects having nearly correct assumed orbits can be easily recovered. Thus, the Kuiper belt has probably taken on an appearance similar to our preconceptions and those objects that may be most unusual and interesting are the ones that have been systematically lost. The following examples illustrate this point and show why dedicated follow-up observations are essential:

- Recovery of the Scattered Disk object (SDO) 1996 TL_{66} was made possible only by early follow-up observations, which were done because it was bright enough to be observed by amateurs.
- Aggressive follow-ups were necessary to recover 2000 CR_{105}. It was far from its predicted position and was only recovered by virtue of a concerted effort. 2000 CR_{105}'s unusual orbit has a 44 AU perihelion and 415 AU aphelion, challenging current dynamical models.
- Theoretical models show that the 1:2 mean motion resonance should be populated. But it took second and third opposition observations to demon-

strate that 1997 SZ_{10} and 1996 TR_{66} occupy this resonance that otherwise appeared to be empty.

If follow-up recoveries had not been made early and often enough, all these objects could very well have joined the ranks of "lost TNOs", and we would have been ignorant of their significance to solar system structure! Indeed, it is likely that many of the lost TNOs were on similarly unanticipated orbits so their initially assumed orbital elements were sufficiently incorrect that casual recovery efforts failed to find them. As the pace of Kuiper belt discoveries increases, the problem of recovery is exacerbated.

To assure recovery, the recovery observations need to equal, or preferably surpass the discovery observations in sensitivity to ensure that lack of recovery is due to ephemeris uncertainties and not due to worse limiting magnitude. Moderate aperture telescopes in the 4 m class are sufficient for both tasks (down to ~24 mag), and their cost effectiveness makes them preferable to larger instruments for discovering and following up the bulk of the ~5000 object sample needed to address the scientific questions posed in Section 3. Very large telescopes are useful for deep studies of size and spatial distribution, but it is unlikely that enough time can be allocated on these instruments to follow more than a small sub-sample of objects.

Establishing a reliable orbit for a newly-discovered TNO generally requires imaging it again a few days after discovery, then again a few months later, and then at least once a year thereafter for a few years until uncertainties in the predicted positions are sufficiently minimized. The recovery rate of TNOs must keep up with the discovery rate in order for discovery surveys to be most effective, and, as described above, the recovery observing plan must be designed to minimize orbital element biases by persevering in searching for objects, even when they are initially not found where they were expected to be. Because total recovery cost is about 5 times the telescope time used to initially discover each TNO, recoveries require a large time commitment on the part of the astronomer (who must quickly analyze the discovery data in order to prepare for the next recovery observations) and on the part of the observatory (which needs to allocate sufficient telescope time for discoveries and subsequent recoveries).

3.2. TNO discoveries

To answer many of the key scientific questions from Section 3, reliable orbits are required for a substantial and unbiased sample of TNOs, which in turn calls for extensive, coordinated search/discovery and recovery/astrometry observations that (*i*) survey a wider fraction of the sky and (*ii*) probe the solar system to greater depths. Two distinct surveys (which we will call "wide" and "deep") are needed. Wide surveys should cover a broad swath of the night sky to a limiting magnitude of ~24 in order to obtain some 5000 TNOs with well-determined orbits and subject to minimal observational biases (other than the obvious magnitude bias). This sample will be used to answer the many question of dynamics, structure, and classification as well as providing a reliable basis set of objects for physical studies. The wide survey effort must be complemented with deep surveys which probe a much smaller portion of the sky to greater depths (e.g., down to ~27$^{\text{th}}$ magnitude) in order to discover and recover a much smaller sample of especially faint TNOs. Deep surveys will illuminate the small-size end of the TNO size distribution and will also enlarge the "known" solar system by pushing its observable frontier outwards from the Sun.

Wide surveys: Wide surveys will play the primary role as we attempt to discern the dynamical structure of the Kuiper belt. The goal should be to discover and get reliable orbits for some 5000 TNOs in the next decade. To meet this objective will require a discovery rate of approximately 700 TNOs per year for the first seven years (the remaining three years are needed to adequately measure the orbits for the last set of discoveries). Objects brighter than $R=24^{\mathrm{th}}$ mag can be detected with moderate-size (~4 m class) telescopes. The ecliptic surface density distribution at this magnitude is approximately 4 TNOs per square degree, and given an effective full width at half maximum of the ecliptic of ~6 °, there are expected to be some 15,000 such TNOs (including objects far from the ecliptic at present), of which the proposed survey would discover about one-third. Although some care must be taken in the planning of the survey to assure that observational biases do not affect the distribution of orbits in the discovery sample, the more critical point where observational biases appear is in the recovery observations, as discussed in Section 3.1.

To estimate the time commitment and facilities needed, we use the following illustrative example (the actual format of the observing plan could differ). If the search were performed at a single telescope during all dark-grey times (±5 nights of the new moon), or 120 nights per year, then the discovery rate would have to be about 6 objects per night (or more, since the galactic plane season may need to be avoided). With an average of ~4 TNOs per square degree, and assuming a survey instrument with a 1 square degree FOV, that would require 2 new search fields per night. Each field would need to be observed 4 to 6 times (2 to 3 times per night on two consecutive nights to verify the object's motion). The final tally would be about 10 to 15 pointings per night on average. Recoveries require a factor of ~5 more observing time, resulting in ~50 to 75 pointings per night during dark-grey times.

Two dedicated 4 m class telescopes, ideally one in each hemisphere, would be able to perform the Wide TNO Surveys efficiently and cost effectively. We strongly recommend that wide-field survey instruments of this type be built and used to discover and follow-up the proposed 5000 TNO sample.

The Large-aperture Synoptic Survey Telescope (LSST) as recommended by the Astronomy and Astrophysics Survey Committee (AASC) in *The Decade of Discovery* report has the potential for making a tremendous impact in Kuiper belt studies. The AASC-endorsed design features a 6.5 m mirror and an estimated $170M price for construction. It would be capable of surveying the entire night sky every week, enabling all ~15,000 TNOs brighter than 24^{th} magnitude to be cataloged and tracked, resulting in unprecedented characterization of the extent and population of the TNOs and their dynamical sub-populations. Many TNOs with unique dynamical and physical properties (wide binaries, extreme colors, and unusual photometric variability) could be identified for further study. However, significant resources must be allocated for the detection and tracking of low apparent motion objects (≤ 3 arcsec/hr) for the LSST to be useful for TNO studies. The Kuiper Belt community recognizes that such a project can be of great benefit to TNO research, but there are major concerns over the endorsement of the LSST: (*i*) If the LSST is primarily designed and implemented by the extragalactic astronomy and/or near-Earth hazard mitigation communities, it is possible that only a small fraction of the LSST time and resources would be available for TNO research or that observing sequences would be poorly optimized for TNO work. (*ii*) Since LSST would not address several essential types of physical observations (e.g., collection of high signal-to-noise broadband colors and lightcurves, near infrared spectrophotometry, and deep "pencil-beam" probes), substantial access to 8 m or larger telescopes will still be required; these two needs could end up competing instead of working together. (*iii*) LSST's construction cost, development time scale, and the fact that it is only a single telescope are difficult to justify when compared with the high cost effectiveness and straightforward engineering of the proposed dedicated pair of 4 m class telescopes. In summary, while the Kuiper Belt community is excited by the prospect of the LSST, the concerns outlined above do not permit the unfettered endorsement of such a project.

Deep surveys: Historically, faint TNOs discovered by deep surveys (sometimes called "pencil beam" surveys) have been lost soon after discovery, so these surveys have yet to achieve their full potential scientific yield. This need not be the case. Deep surveys of the next decade can and should perform the necessary follow-up observations to establish good orbits for at least some fraction of the faint TNOs they discover. Reliable orbits are crucial if faint TNOs are to most usefully constrain the outer solar system's dynamical structure, and thus early history.

While TNO surveys piggy-backing on future space-based wide-field imaging instruments might eventually offer an economical alternative approach to the task of determining orbits for a sample of fainter TNOs (if they do not systematically avoid targeting the ecliptic plane), deep surveys at present require access to the largest ground-based telescopes in the world, and thus are quite expensive. This approach would not be cost-effective for finding the ~5000 orbits needed for dynamical and physical studies.

However, the value of deep surveys for constraining the distribution of smaller and more distant objects is sufficient that they have an important role to play in our exploration of the Kuiper belt. A deep TNO survey probing 3 degree^2 of the sky to a limiting magnitude of $\sim 27^{\rm th}$ magnitude could be expected to find several hundred objects, but following them up as they diverge from the discovery fields would consume more time than is likely to be available on 8 to 10 m telescopes unless a dedicated telescope were built for the project, something which would be an extravagant and inefficient use of the limited resources available for Kuiper belt research. Instead, we must be judicious in applying our very limited large telescope, wide-field imaging resources in the most scientifically productive way we can. Individual search fields should sample various ecliptic longitudes and should not be purely confined to the ecliptic plane. Astrometric follow-up should be primarily directed at particularly interesting objects, such as those discovered at the greatest heliocentric distances. Most importantly, telescope time allocations and funding for deep surveys need to take into account the necessity of doing adequate follow-up observations.

3.3. Observational studies of physical properties

In addition to learning about the dynamics of TNO orbits and their evolution, we have much to learn about the physical and chemical properties of individual objects and about how these properties are related to objects' dynamical histories. At present, we know remarkably little about even the most fundamental characteristics of most known TNOs. We are ignorant of their masses, shapes, albedos, rotation rates, compositions, and internal structures. The observational challenge of answering these questions for a significant sample of TNOs is immense, owing to their extreme distance and faintness. Progress in physical studies of TNOs over the coming decade will depend critically on access to the largest Earth-based, airborne, and space-based telescopes and on the availability of suitable instrumentation at those telescopes. Initially, only the brightest fringe of the TNO population is accessible to many types of observational investigations, but it is essential to survey a less-biased sample, if we are to understand the range of variability among the TNO population, and the differences between different sub-populations. To be effective, these observational efforts must be concurrently supported by a wide variety of laboratory and theoretical studies. Finally, spacecraft exploration of TNOs is needed since many crucial types of data can be obtained no other way.

Visible: It is already possible to do accurate broad-band, standard filter (B, V, R, and I) CCD photometry of TNOs from many larger telescopes. Numerous measurements have been reported, revealing many surprising things, such as a remarkable diversity of colors and large-amplitude lightcurves from objects thought to be much too large to sustain highly irregular shapes. Many, many more observations are needed, in order to reveal how colors, lightcurve amplitudes, etc., correlate with dynamical characteristics for different sub-populations of TNOs. Over the next decade there must be repeated observations of lightcurves and colors for a much larger sample of objects than has been observed to date. Access to CCD cameras mounted on 3 m and larger telescopes in both Northern and Southern hemispheres is essential for the timely acquisition of these data.

Near-infrared: With its plethora of distinctive, strong vibrational absorption bands, the near-infrared wavelength region has the potential to reveal far more compositional information than the visible region. Unfortunately, declining solar flux and increasing telluric sky brightness limit spectroscopic observations to the probably-unrepresentative, brightest fringe of the TNO population at the largest telescopes in the world, at least with the current generation of instruments. Standard broad-band J, H, and K filters permit observations deeper into the TNO population and/or from smaller telescopes, but they are too broad to distinguish distinct molecular absorption features, so they drastically limit the compositional information which can be extracted from this rich wavelength region.

High-throughput, low spectral resolution spectrophotometry is urgently needed. Although technically easy to realize by current instrumentation engineering standards, instruments with the required characteristics are unfortunately not available on any of the world's 6+ m aperture telescopes. Filters which divide each of the J, H, and K transmission windows into several bins would be useful, and instruments that could record all of these wavelengths simultaneously would be ideal, if mounted on 8 to 10 meter (or future, larger) aperture telescopes, with adequate time available to observe a significant sample of TNOs.

Thermal emission: Thermal emission observations are needed to constrain the sizes, albedos, and surface temperatures of TNOs. Their enormous distances from the sun and low surface temperatures make this task an extremely difficult one, but new facilities coming on line over the next decade, including SIRTF, SOFIA, ALMA, and NGST should provide the required capabilities to measure TNO thermal emissions, if we can obtain adequate access to them. Coordinated multi-wavelength visible and thermal observations are preferable for constraining sizes and albedos, and once again, a large, unbiased sample of objects needs to be observed so that patterns can be detected in their ensemble behavior.

In addition to providing information to constrain sizes, albedos, and temperatures, the thermal emission part of the far-infrared spectrum has the potential to provide valuable information on surface compositions. Exploiting this information will require sophisticated space-based instrumentation, as well as more information about the infrared optical behavior of cryogenic materials than is currently available.

Interiors/binaries: TNOs are thought to be primitive bodies, perhaps among the most primitive objects of the solar system. They could still contain ices and organic compounds in proportions little changed since their formation, and thus provide an incredibly valuable window into the chemistry of the outer protoplanetary nebula. Unfortunately, observations of TNO surface reflectance and emission probe only a very shallow surface layer, which is subject to relatively rapid alteration by processes such as photolysis, radiolysis, and volatile loss and thus is unlikely to be representative of TNO interiors.

We want to learn about TNO interiors, but for the next decade at least, we are probably limited to a few spacecraft encounters and to determining masses for the sub-set of TNOs having natural satellites. Discoveries of six binary TNOs have been reported as of early 2002. Combining the masses computed from satellite orbits with thermal determinations of albedos and radii, it is possible to calculate densities for these objects. The possibility of mutual eclipses also offers opportunities to determine individual sizes, densities, and albedos.

Studies of binary TNOs are valuable in other ways as well. By analyzing the ensemble properties of TNO binary orbits, we can compare formation scenarios (e.g., catastrophic disruption from collisions, rotational fission, mutual formation) that would allow us to estimate the number density, size distribution, collisional history, and dynamical evolution of objects in the Kuiper belt region. This in turn would enable us to peer into the formation history of the giant planets and the outer solar system.

Any discovery/recovery observing strategy should include procedures to identify and characterize binary objects. High spatial resolution (sub-arcsecond) imagery is generally needed, and would also be valuable for detecting possible outbursts, perhaps indicating on-going loss of volatile species or impact disruption of volatile-rich subsurface pockets. In addition to continuing the search for

TNOs with satellites, objects found to have satellites need to be aggressively targeted via all available observational techniques.

Comet and Centaur studies: Because many of them originated in the Kuiper belt, and they pass much closer to Earth than TNOs, observational studies of comets and centaurs offer special opportunities to study the compositions and structures of TNOs. Unfortunately, comets and centaurs do not preserve a unique dynamical record of their region of origin, so they cannot be used to directly probe specific sub-populations of the Kuiper belt. Nevertheless, observations of these more nearby objects can reveal unparalleled compositional details, particularly for gas species in cometary comae. Measurements of specific isotopic ratios are also possible, as are sample return missions. A future compositional taxonomy of comets would provide a valuable starting point for efforts to classify TNOs, and it may eventually become possible to link certain types of comets with specific elements of the trans-Neptunian population, by means of compositional markers yet to be discovered.

3.4. Numerical/theoretical models

Much of our current understanding of the Kuiper belt is the result of intense efforts to model their interiors, surfaces, and orbital evolution. Modeling efforts will continue to play a crucial role in unraveling the questions outlined in Section 3, and must be a part of a balanced program of Kuiper belt studies during the next decade. The complexity of present-day models is directly limited by available computing resources, and can be expected to improve significantly as computer technology advances over the coming decade, if equipment upgrades are adequately funded.

Dynamics: Dynamical models have played an important role in our growing understanding of the Kuiper belt. Indeed, the first credible indication of the belt's existence came from efforts to model the origin of Jupiter-family comets in 1988. Models have also led to important conclusions that include: (*i*) orbits in the Kuiper belt are chaotic, (*ii*) the resonant structure of the Kuiper belt most likely has arisen from the outward migration of Neptune, (*iii*) there needed to be roughly 30 Earth-masses of material originally between 30 and 50 AU for large objects to grow, (*iv*) there was a scattered disk (before its discovery) and perhaps a fossilized scattered disk, and (*v*) the anomalously small eccentricity of Neptune may be the result of gravitational interactions with a primordial Kuiper belt. Understanding the origin of the dynamical structure of the Kuiper belt will rely on future dynamical models. These models will require not only simulations of the TNOs themselves, but also of formation and dynamical evolution of the giant planets.

Surfaces: Models of surface and interior evolution are needed to provide understanding of many processes which may have altered TNOs over the age of the solar system. As mentioned earlier, TNOs are relatively pristine remnants of the formation of the solar system. However, to understand what they can tell us about the chemistry of the protoplanetary nebula, we must first understand how they have evolved over the intervening time. Numerous processes are expected to have modified TNO surfaces, including accretion and erosion by impacting particles ranging from dust to many kilometer size, and loss of the most volatile species (such as CO) due to solar heating. Other effects of the radiation environment are also extremely important. In addition to visible solar photons, TNOs are bombarded by UV photons, solar wind particles, cosmic rays, etc., all of which drive structural and chemical evolution of TNO surfaces.

Interiors: The internal structure of TNOs is subject to modification by processes including the propagation of thermal waves, phase transitions such as the crystallization of amorphous H_2O ice, shock waves from large impacts, and effects of radiogenic heating and volatile transport. Efforts to model the influence of these types of processes on TNOs are essential. The possibility of differentiation critically depends on factors such as the amount of ^{26}Al available during and immediately following accretion, which is currently unknown. For C1 chondrite proportions of radioactive elements, coupled thermal and volatile-transport models suggest that the deep interiors of TNOs could be volatile-depleted by radiogenic heat (at least for the most volatile species, like CO) while surface layers could be devolatilized by solar heating. Mobilized species would partially escape and partially re-condense in cooler, intermediate strata, producing a complex layered structure including both volatile-depleted and volatile-enriched regions. These sorts of processes could result in strongly differentiated TNOs, but details are extremely sensitive to factors such as their rates of formation, shapes, sizes, thermal conductivities, porosities, and initial abundances of radioactive elements. Models are needed to explore these dependencies, and to work out probable interior/exterior structures of TNOs as functions of size, heliocentric distance, and rate of formation. Interior models will also be needed to interpret the transition from irregular to spherical shapes, when/if such a transition is discovered.

Radiative transfer: Finally, radiative transfer models are needed to interpret remote photometric and spectroscopic observations. Existing models will require extended capabilities to make them applicable to surfaces having very low albedos and small grain-sizes. Near-infrared reflectances and far-infrared emission have rich potential to provide compositional information about TNO surfaces, but until the necessary models are available, we will be severely handicapped in our ability to extract compositional information from spectral observations in these wavelength ranges.

3.5. Laboratory studies

Both observations and models of TNOs rely on material data from laboratory studies of outer solar system substances at appropriate cryogenic temperatures and thermodynamic conditions. Many critical data have never been measured, or have only been measured under conditions inapplicable to TNOs. Types of measurements urgently needed include measurements of optical, thermal, and mechanical properties, studies of radiolysis and photolysis, and investigations of gas-solid interactions. These measurements will lead to a better understanding of TNO compositions and of surface and internal processes affecting TNOs and can make significant contributions to the key science questions listed in Section 3.

Compositions: To extract compositional information from spectral observations of TNOs, data are needed for the optical properties of candidate species under the temperature and pressure conditions at TNO surfaces. Visible and near-infrared optical constants are needed for interpreting reflectance observations while far-infrared data are necessary for interpreting observations of thermal emission. Data for numerous ices, as well as photolytic and radiolytic products of common ices at TNO surface temperatures are particularly lacking at visible, near-infrared, and far-infrared wavelengths. Various mixtures of different species exhibit changes in the shapes and wavelengths of characteristic absorption bands of their constituent components, and data on these matrix effects are also in short supply.

Surfaces: To interpret color, albedo, or spectral distinctions between TNO classes we will need to understand the processes affecting their surfaces and how these processes modify observable reflectances. Processes expected to play important roles include photolysis, radiolysis, and impact resurfacing. Laboratory investigations of these processes are needed, if we are to interpret observations of the space-weathered surfaces of TNOs. These studies are difficult because time scales differ greatly between the laboratory and the outer solar system, so it is crucial to understand the limitations of extrapolations from laboratory time scales and doses. A better understanding of the chemical pathways whereby products of photolysis and radiolysis react to produce new species will lead to a clearer picture of surface compositions and how those compositions can change with time. Reaction rate constants for specific compounds are necessary for modeling their production over time.

Interiors: As with surfaces, interior compositions and structures result from formation conditions as well as the influence of various processes acting on TNOs subsequent to their formation. Models of these processes (see Section 4.4) depend critically on knowledge of material properties as inputs. Interior thermal and volatile transport models suffer from gaps in fundamental material properties data, with basic thermal parameters, rates of creep, grain growth, and deformation all being poorly constrained. Without appropriate equations of state, it is difficult to predict the results of large collisions in the trans-Neptunian region. Better understanding of the mechanical properties of ice will enable creation of more realistic models of accretion and fragmentation of TNOs. The phase state of H_2O ice is important for determining the amount of volatile gases (CO, CH_4) that may be trapped in the surface. Crystalline ice can effectively trap gases in clathrates in well measured ratios. However, if much of the water ice in TNOs is in the amorphous phase, it is unknown how much gas can be trapped. Since these gases are the source building blocks for complex organics, knowing the amount of gas available and the reaction pathways from photolysis and radiolysis can lead to predictions of abundances of numerous compounds, including many with potential astrobiological significance.

Facilities: Much of the existing laboratory work has been targeted at submicron interstellar dust grains, and thus has concentrated on temperatures too low for TNO surfaces and at mid-infrared wavelengths where reflectance observations of TNOs are nearly impossible. Also, the vast majority of existing studies have been performed on extremely thin (microns thick) films of ice. The physical characteristics of ices change drastically with the sample size, and processes like gas diffusion and radiolysis have length scales much longer than a micron. The H_2O amorphous–crystalline transition temperature appears to vary with the deposition environment and size of the sample. Working with larger samples can be difficult because of the temperature and pressure conditions needed, but these obstacles must be overcome to obtain the data needed for better predictions. Resources will need to be made available for upgrades in laboratory facilities so that the required sorts of studies can be done.

3.6. Environment

Past and present trans-Neptunian environments have yet to be well characterized. In-situ particles, fields, and dust measurements by existing and future spacecraft are essential for learning about this region, and need to be supported (see next section). We do not yet know enough about the environment beyond 30 AU to relate TNO surface properties to environmental factors, such as possible regions of preferential bombardment by dust or larger impactors, episodes of passage through the heliopause, external perturbations (radiative, dust, gas, or gravitational), etc. Observational and theoretical studies of these problems will enable us to understand TNOs in the context of the external conditions they are exposed to.

A potentially key factor in the chemical processing of TNO surfaces is the incidence of cosmic ray energetic particles arising from solar flares, the outwardly expanding solar wind and its heliospheric interaction with the local interstellar medium, as well as external, galactic sources. Expected increases in cosmic ray intensity near and beyond the heliospheric termination shock boundary somewhere near 90 to 100 AU are of special interest for their potential impact on SDOs.

Dust is likely ubiquitous throughout the Kuiper belt due to collisions among TNOs. In-situ dust measurements by spacecraft could conceivably push the solar system's known frontier outward dramatically, and would more firmly establish the suspected connection between Kuiper belts and the dusty disks observed around other stars.

3.7. Spacecraft exploration

The first spacecraft exploration of the Kuiper belt could occur soon after the close of the coming decade, if NASA's Pluto-Kuiper Belt (PKB) mission goes forward in a timely fashion. We endorse this mission vigorously, since it would substantially advance Kuiper belt science in ways completely impossible from Earth-based observations. For instance, spectra obtained by PKB would map regional surface compositions and could perhaps even detect tenuous atmospheres or exospheres. Close-up images revealing surface morphology would shed considerable light on the types and relative rates of processes shaping TNO surfaces. Material excavated in larger impacts could offer unique glimpses into TNO interiors, and comparisons between ejecta from older and younger craters could teach much about the evolution of interior materials following their exposure on TNO surfaces. Observations of the frequency and size distribution of impact craters could reveal the small end of the TNO size-frequency distribution.

As mentioned in the previous section, an on-board dust detector could be used to map the radial extent of the Kuiper belt, and such an instrument would be a valuable addition to the PKB payload. We note that no dust detector was included in the New Horizons proposal selected by NASA for PKB Phase B, and we recommend that one be incorporated into the flight instrument package if possible.

A potential next step after PKB might be the Interstellar Probe (IP) mission, currently under consideration by NASA. IP could completely traverse the Kuiper belt within its mission life span, and thus could offer a great opportunity to learn about radial distributions of dust, particles, and fields, especially in the more distant parts of the Kuiper belt. By extending measurements by the Pioneer, Voyager, and PKB space probes to ~200 AU, Interstellar Probe could investigate the full heliocentric range of space environments affecting surfaces of most known TNOs.

It would constitute a major setback for subsequent decades of outer solar system studies if the PKB mission and its successors were not launched in a timely manner, or if Kuiper belt portions of upcoming missions were de-scoped. We express the strongest possible support for NASA's moving ahead promptly with adequate funding for spacecraft exploration of Pluto and the Kuiper belt beginning with PKB, ushering in a new era in which open competition and new technologies minimize costs while achieving spectacular scientific returns in the outer solar system.