The Solar System Beyond Neptune: Overview and Perspectives

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1. INTRODUCTION

We are in a new era in which the frontiers of our solar system have been completely redefined, thanks to the discoveries of Centaurs and transneptunian objects (TNOs). As of 2007, 15 years after the first discovery, more than 1200 new icy bodies have been detected and observed at increasingly greater distances from the Sun. The discovery of the TNOs resulted in the immediate realization that Pluto is a member of a much larger population. A resolution of the International Astronomical Union (August 24, 2006) defined a new category of objects, the "dwarf planets," and Pluto was recognized as the prototype of this group.

Fifteen years of discoveries and advanced studies give today a completely new view of the solar system beyond Neptune, which has allowed us to develop new models of the formation and evolution of our planetary system. These icy bodies can be considered the remnants of the external planetesimal swarms and they can provide essential information and con-straints on the processes that dominated the evolution of the early solar nebula, as well as of other planetary systems around young stars.

As can be seen in the various chapters of this book, different terms are used in reference to these icy bodies. Many authors use "Kuiper belt objects," as this was the historical terminology used immediately after the first discoveries and is still very common in the literature. Although other names were used, for example, "Edgeworth-Kuiper objects," we prefer and we suggest the use of the more neutral name TNOs to avoid the controversy over who first hypothesized the existence of this population, as described in the "historical" chapter by Davies et al.

The discovery of Pluto by Tombaugh in 1930 triggered early ideas concerning solar system objects beyond the orbit of Neptune, at a time where neither the Kuiper belt nor the Oort cloud of comets was known (although many comets in long-periodic orbits had been observed, e.g., the work of Edgeworth and Kuiper in the 1940s and 1950s). Later, in 1982, a more conclusive study by Fernández and Ip argued for the existence of a source of short-periodic comets close to the ecliptic and beyond the known planetary orbits. About 10 years later, Jewitt and Luu discovered the object 1992 QB_1, now numbered 15670, the first body in a near-circular orbit beyond Neptune. This was an epochal astronomical discovery, since it triggered within a few months the detections of further asteroid-like objects in the outskirts of the planetary system. It did not take longer than two to three years to find the first ~100 distant bodies, representative of a remnant entity from the formation period of the planetary system, i.e., the TNO population. However, the discovery story was — and most likely still is — not yet over, leading to the recognition of a "zoo of transneptunian objects" with distinct orbital and physical properties.

The science of the solar system beyond Neptune is continuously and rapidly evolving. The understanding of this region is one of the most active research fields in planetary science at the present, and many new discoveries can be expected in the coming years. The study of this region and the objects it contains will contribute to the understanding of the still puzzling formation age of the solar system.

2. THE TRANSNEPTUNIAN OBJECT POPULATION

Why do we study the transneptunian population? This population carries the scars of the accretional and evolutionary processes that sculpted the current form of the outer solar system. To understand the history of a rock, the radioactive elements are the most useful, even if they are often a negligible fraction of the total rock mass. Likewise, in our quest to understand the evolution of the solar system, the small bodies appear to provide the richest information, even if their total mass is negligible with respect to that of the planets.

In addition to the physical properties of TNOs, which give us information on the thermal and chemical processes in the outer protoplanetary disk — when and where the objects formed — there are two broad characteristics of the TNO population that give us fundamental clues to unveil the history of the solar system: the size distribution and the orbital distribution.

Determining the orbits of TNOs is made difficult by their faintness and the associated complications in following them for several months. The specific difficulties and problem solutions for the orbit determination of TNOs are presented in the chapter by Virtanen et al. These objects, by definition (and unlike most other solar system bodies), are observed only over very short orbit arcs. Here one should remember that Pluto has moved only 155° in true anomaly since its discovery, i.e., less than 45% of its orbit around the Sun. Hence, specific methods for orbit determination are developed, allowing statistical predictions of ephemeris uncertainties that can help improve the orbital parameters by new measurements. Nonetheless, a substantial fraction of the discovered bodies are not reobserved early enough to ensure future secure recovery, and many objects are still lost.

The size distribution of TNOs is reviewed in the chapter by Petit et al. It is now certain that the size distribution of TNOs is very steep at the large size end. The exact value of the exponent of the differential distribution is still debated, but should be between –5 and –4. Pluto and its companions of comparable size fit this single-slope power law. Therefore they appear not to be a special category of objects, but rather the largest statistical members of the TNO population. The steep size distribution cannot extend indefinitely to small sizes, otherwise the total mass of the population would be infinite. Therefore, the size distribution has to "roll over" toward a power law with a shallower slope. The size at which the change in the power-law exponent occurs is a subject of debate. Previous work, using published results and new HST observations that showed a deficit of objects at apparent magnitude ~26, claimed that the rollover is at a diameter range of about 100–300 km. The authors of the Petit et al. chapter challenge this conclusion, presenting new observations that show a unique power law distribution up to magnitude 25–25.5. Settling this controversy requires a larger statistical dataset that will become available with the observations enabled by a new generation of instruments (see the chapter by Trujillo et al.).

The current uncertainty in the size distribution of TNOs does not allow a precise assessment of the total mass of the population. Current estimates range from 0.01 to a few times 0.1 $M_\oplus$. Upper estimates on the total mass also come from the absence of detected perturbations on the motion of Neptune and of Halley-type comets. Whatever the real value, it appears low (by 2 to 3 orders of magnitude) with respect to the primordial mass in the transneptunian region inferred from a radial extrapolation of the solid mass contained in the giant planets. In terms of mass deficit, therefore, the transneptunian region is similar to the asteroid belt.

The steep size distribution at large sizes is usually interpreted as a signature of the accretion process, whereas the shallower slope at small sizes is expected to be the consequence of collisional erosion. The accretion/erosion process is reviewed in the chapter by Kenyon et al. Their chapter explains that the two processes occur contemporaneously. While the larger bodies are still growing, they excite the orbital eccentricities and inclinations of the small bodies, whose mutual collisions start to become disruptive. Because the dispersion velocity of the small bodies is on the order of the escape velocity from the largest bodies, the system is always on the edge of an instability. If some processes (collisional damping, gas drag, weakened solar radiation due to the low optical depth of dust population) reduce somewhat the dispersion velocity of the small bodies or the evacuation rate of the dust, then accretion wins and a substantial fraction of the total mass is incorporated in large, unbreakable bodies. If, conversely, some external perturbation (from a fully grown planet or close stellar passages) enhances the velocity dispersion, then the accretion stalls, and most of the mass remains in small bodies, is eventually ground down to dust size, and is then evacuated by radiation effects. The simulations presented in the Kenyon et al. chapter suggest that in the transneptunian region most of the mass remained in small bodies and that, consequently, the mass deficit of the TNO population was caused primarily by collisional grinding. These same simulations predict the formation of a few Pluto-sized bodies as the largest members of the TNO population. However, several lines of evidence argue in favor of the past existence of 100–1000 Pluto-sized bodies in the planetesimal disk. Strictly speaking, these lines of evidence apply to the planetesimal disk in the region of the giant planets, and not in the transneptunian region. If this is really the case (many large bodies in the inner part of the disk and most of the mass in small bodies in the outer part), the origin of this drastic change of size distribution with heliocentric distance remains to be understood. It should also be noted that current coagulation models fail to produce the cores of the giant planets.

The complex orbital structure has prompted astronomers to divide the transneptunian population into subclasses, often defined slightly differently and given different names in different papers. The chapter by Gladman et al. aims to bring some order and consensus to the classification of TNOs. The authors of the chapters in this book have tried to adopt the Gladman et al. nomenclature and definitions, although this has not always been possible. The idea behind the approach of Gladman et al. is to have a classification that reflects what we see today, making an abstraction of formation and orbital sculpting models that might be largely trusted today but will be discarded in the future. Of course, this is a difficult exercise, because what we actually see when looking at the orbital distribution is inevitably influenced by what we think generated that distribution.

The chapter by Gladman et al. is logically paired with the chapter by Kavelaars et al. on the orbital distribution of TNOs. A crucial issue addressed in that chapter is the understanding of how the orbital structure of the TNOs discovered so far is influenced by observational biases. Some biases are easy to model, in principle; they depend on the pointing history and limiting magnitude of the surveys. Unfortunately, this information is not available for many surveys, in particular those from the early years of TNO discoveries. Other biases are more subtle. For instance, objects that receive incorrect provisional orbits might not be recovered later because of the wrong ephemeris, and therefore are lost. The objects that are not lost are those for which the provisional orbits are correct. In such a circumstance, the resulting catalog of transneptunian orbits looks extremely similar to what the person assigning provisional orbits had in mind! Luckily the situation is not that paradoxical. Modern (and future) surveys give special attention to careful followup of the discovered objects in order to be able to determine the orbits accurately, without the need of *a priori* assumptions. Thus, today some features in the picture of the orbital structure of the transneptunian population appear secure and not due to biases. We will return to these features in section 4.

3. TRANSNEPTUNIAN OBJECT PHYSICAL PROPERTIES

Knowledge of the composition and properties of these icy bodies forming the TNO population would help in better understanding the processes that shaped the solar nebula at large heliocentric distances and that determined the formation and evolution of the planets.

The availability of very large groundbased telescopes (8 and 10 m) and telescopes in space (the Hubble and Spitzer telescopes), equipped with modern sensors in many wavelength regions, has enabled observational studies of the physical properties of a significant number of TNOs. In addition to information about surface composition, the observations have given us fundamental information about the bulk properties of several TNOs. Those properties include the size, shape, presence of satellites, and in some instances the bulk density and porosity. Knowledge of bulk properties is critical to an understanding of the origin and evolution of TNOs.

Photometric observations over time can give insight into the shape of a solar system body that is too small or distant to be seen with any spatial resolution, and nearly a century of electronic photometry with telescopes has taught astronomers how to do this well. Seen from Earth, an object of spherical shape and uniform surface brightness will give a steady brightness as it rotates, while an irregular shape (or nonuniform surface brightness) will result in a lightcurve of variable brightness over time. Experience has shown that the largest bodies have near-spherical shapes and that their variable lightcurves result from an irregular surface brightness (e.g., Pluto). Somewhat smaller bodies have irregular shapes, and those shapes, rotation periods, and orientation of the spin axes can be determined from precision photometric measurements made over time. In their chapter, Sheppard et al. have analyzed the rotation periods and photometric ranges of a number of TNOs, Centaurs, and main-belt asteroids, and show that some objects are spinning so fast that their equilibrium shapes are considerably elongated. The measured rotation periods of TNOs larger than about 50 km in radius range from about 3 to 18 h, with the peak in the frequency distribution at 8–9 h; there is very little information on smaller objects in the TNO population. Objects less than about 50 km in radius are expected to be collisional remnants, with irregular shapes generated at the time of disruption of the original body.

The size of a KBO can be estimated from a measurement of the brightness of the sunlight reflected from it, but only if the reflectance (albedo) of its surface is known. In cases where both the reflected light and the thermal radiation at long wavelengths can be measured, it is possible to calculate both the dimensions of the object and its surface albedo. This "radiometric technique" has been extensively used in asteroid studies, and is well calibrated from many independent measurements of the sizes of asteroids. Transneptunian objects are very cold (~30 to 50 K) because of their great distance from the Sun, and consequently their thermal radiation is very weak and reaches its blackbody peak at a wavelength near 100 μm. Long-wavelength thermal emission can be measured in a few wavelength bands from Earth-based telescopes, but the most sensitive telescope used in this work is the Spitzer Space Telescope, with capabilities to detect exceedingly weak radiation at 24 and 70 μm. For approximately 40 Centaurs and transneptunian objects, the thermal emission at one or both of these wavelengths has been measured by Spitzer, and the sizes have been derived from these and groundbased measurements of the visible radiation (reflected sunlight). Their dimensions are thus known with precision on the order of 10% or 20% (see chapter by Stansberry et al.), and their surface albedos are seen to range widely from about 3% to 85%, with most objects having low values.

Patterns have begun to emerge from statistical studies of albedos and colors, such that the redder TNOs and Centaurs have higher albedos than those with more neutral spectral reflectances. Additionally, albedo appears to be correlated with an object's mean heliocentric distance, diameter, and spectral reflectance. Several possible trends of colors and orbital elements are described in the chapters by Doressoundiram et al. and Tegler et al. In particular, there is a well-known correlation between color and orbital inclination. Highly inclined classical objects have diverse colors ranging from gray to red, while low-inclination classical objects are mostly very red. The significance of these relationships in terms of the origin, evolution, and space environment of TNOs and Centaurs has only just begun to be explored. A taxonomic scheme based on multivariate statistics (see chapter by Fulchignoni et al.) is proposed to distinguish groups of TNOs having the same colors. The differences among these groups could provide some evidence on the evolution processes affecting the TNO population. The effect of the phase angle on the photometric and polarimetric data to analyze the properties, such as grain sizes and albedo as well as porosity of the surface material, is reviewed in the chapter by Belskaya et al.

Satellites have been detected for several TNOs and a few Centaurs using optical methods of high-resolution imaging. Most TNO satellites have been found with the Hubble Space Telescope (see the chapter by Noll et al.), while adaptive optics with groundbased telescopes (e.g., Keck) has revealed others. When the orbital period and distance of the satellites can be determined, the mass of the primary body can be calculated from Kepler's third law, and the mass of the satellite can be estimated. Nearly 10% of the TNOs studied at high spatial resolution from groundbased telescopes have one or more known satellites. Pluto has three known.

In a few cases, TNOs having satellites are also sufficiently large to be detected at thermal wavelengths, as with the Spitzer Space Telescope. In those special cases, it is possible to combine the mass determinations with the size of the body in order to calculate its mean density. The mean density is reflective of the internal composition, particularly the relative fractions of ices, rocky material, and metals, as well as the porosity. Similar information on mean density and porosity has become available for a few asteroids and comets, making it possible to compare small bodies originating in both the outer and inner regions of the solar system. The calculated densities of TNOs have surprised investigators by their wide range, from ~0.5 to nearly 3 g/cm^3. Pluto's density is 2.03 g/cm^3, corresponding to an internal mix of rock and ice. The TNOs with densities less than 1 g/cm^3 are presumed to be porous to varying degrees. In some cases, e.g., (47171) 1999 TC_{36}, the low density requires that some 50–75% of the interior consists of void space.

Many of the bulk physical properties of TNOs carry important implications for their origin and evolution. The occurrence of binaries, for example, cannot be explained by close encounters or collisions in the TNO population that presently exists. Instead, it appears to be a remnant of the early, larger, population in which multiple encounters and mutual collisions were far more frequent than is possible today. The wide range in mean density of TNOs and Centaurs challenges us to explore scenarios of formation, collisional history, and internal thermal processing. Concurrent discoveries about the physical properties and compositions of comets, presumed to originate from the Kuiper belt, have given surprising results on the heterogeneity of these bodies, which include large fractions of high-temperature minerals from regions in the solar nebula closer to the Sun than Mercury, as well as materials representative of condensation at large heliocentric distances.

Observational studies of the compositions of TNOs, Centaurs, and the comets that came from the Kuiper belt depend on high-quality observational data, mostly obtained with groundbased telescopes. The most diagnostic spectroscopic information occurs in the near-infrared, with the spectral region at 1.0–2.5 μm carrying much of the information about ices and some minerals in the surface layers of these objects. Fortunately, this spectral region is readily detectable with groundbased telescopes. However, remote sensing observations are limited to probing only the "optical" surfaces of TNOs, and the subsurface composition must mostly be inferred rather than measured directly. Larger telescopes and improving spectrometers continue to expand the range of objects that can be observed, but a fundamental limitation outside the observatory is the paucity of laboratory spectroscopic data on candidate materials on the surfaces of TNOs, Centaurs, and comets.

Recently surveys of TNOs have begun to reveal objects of comparable and even larger size than Pluto. Most of the large TNOs are sufficiently bright for detailed physical study and most of the TNOs, like Pluto, have unique dynamical and physical histories (see chapter by Brown). As a whole, the largest TNOs appear to be more diverse in surface composition, presence of satellites, and density. It is probable that about three more TNOs of large size await discovery, but perhaps tens to hundreds more can exist in the distant region where Sedna resides during its 11,000-year orbit. Among the large objects detected, Sedna appears dynamically distinct from the entire transneptunian population. It has a perihelion beyond the main concentration (more than twice the semimajor axis of Neptune) and an extreme eccentric orbit with an aphelion at 927 AU.

Although the discovery of such objects presages a large population in the distant region, no surveys for fainter objects have yet succeeded in detecting such distant objects. The four largest known TNOs (Eris, Pluto, Sedna, and 2005 FY_9) have surfaces spectrally dominated by frozen methane, but the surface characteristics differ on each body. Eris is currently the largest known object of the population, with a remarkably high albedo of about 0.87, and a satellite, named Dysnomia.

The most striking difference between the largest TNOs and the remainder of the population is the presence of volatiles in the spectra of the large objects compared to relatively featureless spectra of the smaller ones. All the large objects show the presence of some ices on their surfaces.

Investigations of the surface compositions of TNOs and Centaurs consist of measurements of color, i.e., the shape and slope of the spectral energy distribution of reflected sunlight, and spectroscopic observations aimed at the detection of specific molecules and minerals (see chapter by Barucci et al.). The enabling laboratory data for ices, minerals, and refractory organic materials consist of a miscellany of spectra and optical constants (complex refractive indices) obtained at various spectral resolutions over various wavelength intervals. In many cases the resolution and wavelength regions are inadequate or inappropriate for the observational data at hand, and since the observations cannot be made at any arbitrary resolution or spectral region, it is essential that the laboratory data be taken under the appropriate conditions and in the appropriate ways. The chapter by de Bergh et al. gives an extensive review of the available laboratory data for candidate materials found or expected on the surfaces of TNOs and Centaurs, and identifies the gaps in available information. As they note, the complex refractive indices of ices, organic materials, and minerals are of special importance because they are used in radiative transfer model calculations of synthetic spectra to match the observational data. These indices are often very difficult to measure, but their importance is underscored by the successes that have been achieved in modeling TNO and Centaur spectra, sometimes with as many as five different materials.

In their chapter, de Bergh et al. emphasize the nature and importance of complex refractory organic solids, because for some outer solar system bodies with especially red colors, only these organics have been able to match the spectral characteristics obtained at the telescope. Imperfect and imprecisely diagnostic as they are, a class of refractory organics called tholins has proven to be the organic material of choice in modeling the surfaces of outer solar system bodies, in part because they are the only materials for which reliable optical constants are readily available. Whatever their limitations, the tholins are found to account for the colors of a great many bodies in the solar system, including planetary satellites, certain asteroids, Centaurs, and TNOs.

4. PHYSICAL PROCESSES

The TNO population embraces the most pristine objects in the solar system, but over the course of 4.5 G.y. they have suffered various weathering processes, including damage from cosmic rays and ultraviolet radiation, sputtering and erosion, and mutual collisions. An understanding of all these processes is critically important to the interpretation of the surface compositions and the internal compositions and structures of the TNOs.

The surface structure and chemistry of a TNO or Centaur is affected by the aggressive attack by energetic phenomena in the space environment, with the result that molecular complexes are structurally changed and the molecular compositions of ice and minerals are altered over time. Laboratory experiments on a variety of appropriate materials, irradiated by energetic particles that simulate the space environment, are described in the chapter by Hudson et al., who show how molecular transformations lead to the production of different components when (primarily) ices are irradiated. This topic is in its infancy, and as it develops, it is certain to produce results important and relevant to the study of TNOs and Centaurs.

Collisions are very important for the evolution of TNOs, as is evident from the occurrence of interplanetary dust particles and the size distribution and total mass of the TNOs. In their chapter, Leinhardt et al. analyze the physical effect of collisions, describing recent advances on the effects of collisions by laboratory experiments and new numerical simulations. Their chapter discusses possible relevant consequences of collisions as they pertain to the alteration of the surface properties and the modification of the internal structure of the target. Collisions are relevant both to small and large objects. The moons of Pluto are modeled to have been formed from a disk of debris ejected during the collision of Pluto with a projectile of almost equal size, in a process similar to that of the formation of Earth's Moon. Very recently, the first collisional family has been discovered in the transneptunian population, associated with the nearly Pluto-sized body (136108) 2003 EL_{61}. This object is an anomalously fast rotator, has an unusually high density, and has two satellites. These features alone suggested that 2003 EL_{61} was originally a body with a high-density rocky core and a low-density icy mantle that suffered a giant collision that spun it up and ejected a large fraction of the mantle into space. Now, five other objects, with diameters ranging from 150 to 400 km, have been identified to be tightly clustered in orbital space around 2003 EL_{61}. These objects share the same physical properties: an icy surface whose spectrum shows deep-water absorption bands and a "gray" color. No other object in the TNO population has both these properties (see chapters by Brown and Barucci et al.). Altogether, these aspects make this collisional family a very compelling case: a unique "beast" in the solar system, given that no family in the asteroid belt contains objects of comparable sizes.

Very little is known about the internal structure of TNOs although they are presumed to display great diversity. The interplay between the effects of solar heating and internal heating in bodies with different initial conditions can result in completely different configurations. In their chapter, Coradini et al. investigate the thermal evolution of these bodies, and how and when it can procede to internal differentiation. By estimating the presumed surface expressions of differentiation and evolution of a TNO, the authors try to link the surface properties with those of the interiors. In particular, they investigate the link with the comets, and they conclude that the great variety observed in comets can either reflect their initial compositions or can be related to the collisional disruption of previously differentiated bodies, thus giving rise to objects with different volatile content.

The presence of some ices on the surfaces of all large TNOs indicates that space weathering and collisional resurfacing are not the only mechanisms that can affect the surface properties, and probably some internal geological activity such as cryovolcanism should be considered. The detection of surface volatiles and high albedos on some TNOs indicates the possible existence of atmospheres, at least as transient phenomena on other TNOs in addition to Pluto. The structure of a TNO atmosphere will depend on the distance from the Sun, the atmospheric composition, internal radiative transfer, and many other physical processes. As described in the chapter by Stern and Trafton, the principal requirement for atmospheric formation on transneptunian objects is the presence of gases or sublimating/evaporating materials on or near the surface. In the case of low-gravity bodies such as TNOs, which have prodigious atmospheric escape rates, it implies some resupply mechanism to the surface, such as internal activity, or the import or excavation of volatiles by impactors.

Outgassing from the interior is another important process, not only because of the high volatile content of TNOs, but also because they may be unusually porous (see the chapters by McKinnon et al. and Coradini et al.). Such porosity increases the conductivity of volatiles to the surface and therefore the effective size of the reservoir that supports an escaping atmosphere or coma. The importance of internal release, from the near surface (as for the geysers of Triton and Enceladus) or from deeper inside, should not be underestimated.

5. FORMATION AND EVOLUTION

Beyond Neptune, but inside the Oort cloud, we note there are two major populations, each containing a comparable number of objects. One group, called the scattered disk, occupies unstable orbits scattered by Neptune; another group has orbits that are stable, at least on timescales of several billions of years. The latter can be subdivided into a resonant population (inhabiting major mean-motion resonances with Neptune) and a classical population (not affected by any notable resonance). To make things more complex, there is also a stable population of objects whose distribution is remarkably similar to that of the scattered disk. This population is called "detached" (sometimes "fossilized" or "extended scattered"). Whereas the scattered disk and the detached population span all values of semimajor axis (with larger eccentricities for larger semimajor axes), the classical population is sharply bounded at 48–50 AU. Something happens there; either there is a sharp drop in the density of the population (an outer "edge"), or a sharp change in the size distribution (all objects beyond this limit being too small — or, less likely, too dark — to be detected by current surveys).

The eccentricities of the resonant population can be as large as 0.3 or 0.4. In fact, resonant objects are stable even if they are Neptune crossers (within some limits), thanks to the stabilizing effect of resonant dynamics. Conversely, the eccentricities in the classical population are bounded to the range 0.1–0.2 (depending on semimajor axis). In fact, with larger eccentricity values, the objects would be scattered by Neptune. A remarkable feature is that the eccentricity distribution in the classical population does not peak at zero.

For semimajor axes up to 45 AU, the eccentricity distribution is rather flat in the allowed stability range. Between 45 AU and the edge of the classical belt, there is even a deficit of low-eccentricity objects! Finally, the inclination distribution in the classical belt is bimodal. About half the population has a peaked inclination distribution in the range 0°–4°, and the remainder has a flat inclination distribution ranging up to 35°. These two subpopulations with small and large inclinations are called "cold" and "hot," respectively. Curiously, these subpopulations seem to have different physical properties. Their colors are different (see the chapter by Doressoundiram et al.), as are their size distributions (see the chapter by Petit et al.).

The theoretical models of the origin of the orbital structure of the transneptunian population are reviewed in the chapters by Gomes et al. and Morbidelli et al. The former focuses on the scattered disk and the detached population. It reviews the dynamics of the scattered population, characterized by several episodes of trapping into mean-motion resonances with Neptune of even larger order. It demonstrates that the current scattered disk should be the remnant of a much more populated structure, formed when Neptune scattered away the planetesimals from its neighboring region. Gomes et al. also show that the scattered disk, not the classical or the resonant populations, is the source of Centaurs and Jupiter-family comets, and they also discuss a possible connection between scattered disk and Halley-type comets. Finally, they address the origin of the detached population during a primordial phase in which Neptune's orbit was still evolving (expanding and with possible large changes in eccentricity) due to the interactions with the other planets and with the neighboring planetesimals.

The chapter by Morbidelli et al. focuses on the classical and the resonant populations. First, it reviews the now "classical" model of Neptune's migration and the origin of the resonant populations, and then addresses the issue of formation of the outer edge of the classical belt, presenting the various models proposed so far. Finally, Morbidelli et al. come to the problem of the mass deficit of the transneptunian population, arguing in favor of an alternative solution to the collisional grinding scenario presented by Kenyon et al. They propose that the original planetesimal disk had an outer edge somewhere around 30 AU (which helped stabilize Neptune at its current location). The objects that we see today in the classical population would have formed within 30 AU and implanted into their current region during a chaotic phase of the evolution of the giant planets. If this view is right, the current low mass of the transneptunian population is not due to the elimination of mass from the 40–50-AU region, but to the low efficiency of the implantation process from the inner part of the disk.

What emerges from the chapters by Gomes et al. and Morbidelli et al. is the ambition to explain the current structure of the transneptunian population in the framework of a unitary model of evolution of the solar system. The model that is presented — called the Nice model — aims to simultaneously explain the current orbits of the giant planets, the capture of their irregular satellites, the late heavy bombardment of the Moon, the properties of the transneptunian population, and the origin of the Trojans of Jupiter and Neptune. Time will tell whether this model will stand as a template for our view of solar system history, or will eventually fail in the light of some discovery that it cannot explain.

Somewhat related to the Gomes et al. chapter is that by Duncan et al., devoted to the origin of the Oort cloud. The Oort cloud is in some sense the distant end of the scattered disk, perturbed by passing stars and the galactic tides. The Duncan et al. chapter reviews the reference formation model and the remaining open problems. The discovery of Sedna, with a semimajor axis of roughly 500 AU and a perihelion distance of ~80 AU, brought about a real revolution in our view of the Oort cloud structure and of its formation. Sedna could be considered as a member of the detached population. However (as shown in the Gomes et al. chapter), the models that successfully reproduce the distribution of the detached population at smaller semimajor axes fail to explain the origin of the orbit of Sedna. The fact that no objects have ever been discovered with a perihelion distance comparable to that of Sedna but with a much smaller semimajor axis (despite the more favorable observational biases) suggests that Sedna is actually at the edge of the inner Oort cloud (see also the nomenclature chapter by Gladman et al.). The extension of the inner Oort cloud down to 500 AU in semimajor axis places an important constraint on the galactic environment in which the solar system formed. This feature is successfully reproduced by postulating that the Sun formed in a cluster with a central density of gas and stars on the order of 10^4–10^5 $M_\odot$ per cubic parsec. These densities compare well with those observed in young stellar associations that are a few million years old, and are slightly lower than that of the Trapezium region in Orion. Thus, the Sun should have formed in a quite typical environment and not as a rare, isolated star.

6. LINKS WITH THE OTHER POPULATIONS, BOUNDARIES, AND COMPARISON WITH OTHER STELLAR SYSTEMS

Although this book is devoted primarily to the transneptunian population, we also explore the interrelationships between TNOs and other populations inside Neptune's orbit, such as the Centaurs, Jupiter Trojans, etc. We also must consider the question of "What is the boundary of our solar system?" and the effects on TNOs (including comets) caused by the interactions between our solar system's boundary and interstellar space. Of particular fascination is how our solar system appears from afar, and therefore, how might we recognize "Kuiper belts" or "Oort clouds" around other stars that are similar to or different from our own.

In a "traditional" view, where the jovian Trojans formed around Jupiter's orbit and the irregular satellites were captured from the regions in the vicinity of the giant planets, the similarities among Trojans, satellites, and TNOs tell us that the primordial planetesimal disk had quite uniform physical properties with respect to heliocentric distance, at least beyond the so-called snowline (the distance at which water vapor condenses as ice). The differences just remind us that the disk could not be *totally* uniform. In the view of the Nice model, Trojans, satellites, and TNOs are all captured into their current residence regions from an annulus of planetesimals roughly between 20 and 30 AU.

The Oort cloud would have been assembled in two stages. In the first stage, occurring immediately after giant planet formation when the Sun was presumably in a dense galactic environment, the inner Oort cloud formed from the planetesimals within 20 AU. Sedna should have been emplaced onto its current orbit during this stage. The second stage occurred when the 20–30-AU planetesimal annulus was dispersed at the time of the late heavy bombardment, and resulted in the formation of the outer Oort cloud (see chapters by Duncan et al. and Gomes et al.).

Thus, through the interrelationships in their formation scenarios, the resulting similarities are obvious: these objects are just brothers and sisters. The physical differences need to be explained by the different evolutionary paths that the three categories of objects followed to reach their current orbits. For instance, Trojans do not have extremely red colors, unlike TNOs. But the nuclei of Jupiter-family comets also do not show extremely red colors, although we are confident that they come from the Centaurs (characterized by a bimodal color distribution), which in turn come from the scattered disk (characterized by a mixed variety of colors). In conclusion, studying similarities and differences between TNOs and other populations inside Neptune's orbit is interesting, although the interpretation is model-dependent. In principle, a deep understanding of differences and similarities might help us in discriminating among different views of the origins of these populations.

The chapter by Nicholson et al. focuses on the irregular satellites of the giant planets, reviewing the observational efforts that made their discovery possible, the satellites' orbital distribution, and their physical properties. Finally, it discusses merits and drawbacks of the various capture mechanisms proposed so far, including the Nice model.

The chapter by Dotto et al. reviews the orbital and physical properties of the Trojans of Jupiter, noting similarities and differences with both primitive asteroids and TNOs. While the actual relationship among irregular satellites, Trojans, and TNOs is still debated, the Jupiter-family comets (see the chapter by Lowry et al.) are believed with confidence to be representatives of the *in situ* unobservable population of kilometer-sized TNOs. These comets escaped from the transneptunian region and were transported into the inner solar system by the combined scattering actions of the four giant planets. Hence, the physical properties of the Jupiter-family comets can help to illuminate and understand those of the more distant companions remaining in the transneptunian region, in particular since the former are easier to observe from Earth and have even spacecraft measurements available.

An interesting (although for the moment still debatable) scenario for links with other solar system bodies is illustrated in the chapter by Gounelle et al., i.e., meteorites from the outer solar system. Here, in particular the CI1 chondrites are suspected to originate from the population of Jupiter-family comets, which, in turn, as we have seen, are dynamically linked to the transneptunian population. Hence, CI1 chondrites can provide information on the physico-chemical properties and constitution of matter in the outskirts of the planetary system. An intriguing finding from the CI1 chondrites is the indication of hydrothermal alteration of the material, implying that their parent bodies experienced physical conditions leading to the presence of liquid water in their interiors.

Last, but not least, the collision history of the Kuiper belt calls for the existence of a dust cloud at larger heliocentric distances, a debris disk entity that can also be observed around some other stars. With a production of ~10^{15} g/yr of dust (measured from the two Pioneer spacecraft), the transneptunian population is probably the main generator of small particles in the solar system, slightly exceeding the combined roles of the asteroid belt and of sublimating comets in the inner solar system. The evolution of the dust generated in the transneptunian region is reviewed in the chapter by Liou and Kaufmann. The dust particles that are sufficiently large not to be blown away by radiation pressure spiral inward under the Poynting-Robertson drag effect. Like comets, most of the dust is eventually scattered into hyperbolic orbits during close encounters with the giant planets. However, a fraction of the dust population manages to pass through the giant planet system in a relatively unperturbed manner, and penetrates into the inner solar system with orbits characterized by moderate eccentricities and inclinations, quite typical of the dust particles produced in the main asteroid belt. Liou and Kaufmann estimate that the dust produced in the transneptunian region contributes up to 5% of the dust flux at 1 AU.

Beyond Neptune, the steady-state distribution of the transneptunian dust does not have a cylindrical symmetry. It has specific azimuthal structures that would reveal the presence of Neptune to a putative observer from outside the solar system. The connection between the transneptunian dust and the debris disks observed around other stars is discussed in the chapter by Moro-Martín et al. Of course, the debris disks that we observe are much more massive than the current transneptunian dust disk, and probably correspond to the phase when the transneptunian planetesimal population was much more numerous than now. Frequently they show structures in the disk light distribution — such as spirals, rings, and clumps — that are interpreted to originate from collision events. The detection of inner cavities and brightness asymmetries and other features in disks might be a signature for the presence of massive planets shaping the disk geometry through their gravitational interaction. Many disks do not show solid-state features, indicating that the particles therein are larger than 10 μm in size. A few disks, however, display strong silicate emission that might be due to the release of small grains ejected by collision events of major planetesimals in the disk.

Finally, our view of the solar system beyond Neptune must consider where our solar system ends. The outermost nongravitational influence of our solar system on the galaxy comes from the Sun's magnetic field and the outflow of the solar wind. In essence, these create a "bubble" in interstellar space, within which our solar system resides. Outside this boundary, called the heliopause, one finds the interstellar medium. The chapter by Richardson and Schwadron examines our current knowledge of the heliopause and its probing and eventual crossing by the (hopefully) still transmitting Voyager spacecraft. At that time we will know directly that for the first time an object mady by human beings has left our solar system and entered interstellar space.

When Edgeworth and Kuiper conjectured the existence of a belt of small bodies beyond Neptune, they certainly were imagining a disk of planetesimals preserving the pristine conditions of the protoplanetary disk (e.g., extremely small orbital eccentricities and inclinations). But, since the first discoveries of transneptunian objects, astronomers have realized that this picture is not correct; the disk has been affected by a number of processes that have given the population a very complex structure. As we anticipated above, this structure can potentially help us to unveil what actually happened out there, and in turn understand how the giant planets of the solar system formed and evolved.

7. PERSPECTIVES

The last section of the book provides perspectives for the future and new directions for the exploration of the transneptunian region. Unlike the surveys performed up to now, future survey projects (see the chapter by Trujillo) aim at a near-complete coverage of the transneptunian region that is within the reach of 2–8-m-class groundbased telescopes. Not only will the instrumentation enable the discovery of a tremendous number of new objects, but it will also provide high-quality orbit determinations (enabling proper dynamical analysis), and it will facilitate measurements of their physical properties. A putative population of small and very distant objects that are invisible to conventional Earth-based observations because they are too faint might be detectable through occultations of background objects, through a new observing option described in the chapter by Roques et al. In fact, this method could enable the investigation the subkilometer-sized population of the TNO size distribution, as well as the outer regions of the Kuiper belt.

Stellar occultations observed from Earth are also probably the most powerful tool available for the detection of TNO atmospheres. Although occultations are capable of revealing atmospheres down to microbar pressure levels, stellar occultations by TNOs are rare because of their tiny angular sizes and uncertainties in the knowledge of their orbits. Further in the future, the American-European-Chilean-Atacama Large Millimeter Array (ALMA), the Cornell Caltech Atacama Telescope (CCAT), and the joint ESA/NASA Herschel mission could be used for a large survey of 100-km-class-sized TNOs.

And finally, NASA's *New Horizons* spacecraft is already on its way to Pluto-Charon. In 2015 its instruments (see the chapter by Weaver et al.) will completely open new insights into the physics and chemistry of these two Kuiper belt representatives, no doubt disclosing many of the secrets of these bodies that only an *in situ* investigation can reveal. And with some luck *New Horizons*, after its visit at Pluto-Charon, will have the opportunity to fly by one or more so-far-undetected Kuiper belt objects farther along the road to the outskirts of our planetary system.