J.K.Davies, J. McFarland, M.E. Bailey, B.G. Marsden, W.-I Ip, 2008. In "The Solar System Beyond Neptune", eds. M. Antonietta Barcci, Hermann Boehnhardt, Dale P. Cruikshank and Alessandro Morbidelli, pp. 11–23. © University of Arizona Press, Tucson, Arizona, USA.

The Early Development of Ideas Concerning the Transneptunian Region

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We review the history of the prediction of, and searches for, a population of comets and transneptunian planetesimals. Starting with initial speculations before and after the discovery of Pluto, we examine various predictions by Edgeworth, Kuiper, and others on the existence of such a population and review the increasingly sophisticated theoretical efforts that eventually showed that the number of short-period comets requires that an ecliptic transneptunian population exists. We then recount various search programs that culminated in the discovery of the first few transneptunian objects and led to the realization that this region is dynamically much more complicated than first suspected and has important links both to Centaurs and the dense inner core of the Oort cloud.

1. REACTIONS TO THE DISCOVERY OF PLUTO

"In the little cluster of orbs which scampers across the sidereal abyss under the name of the solar system there are, be it known, nine instead of a mere eight, worlds." Datelined Flagstaff, Arizona, March 13, 1930, the seventy-fifth anniversary of the birth of its founder, this announcement from the Lowell Observatory via the Associated Press was brilliantly concocted. It could hardly fail to attract the attention of the educated population of the third of those worlds. It did not matter that the subhead in the next day's *New York Times* to the effect that "The Sphere, Possibly Larger than Jupiter and 4,000,000,000 Miles Away, Meets Predictions" represented a gross misinterpretation of the truth. The Lowell Observatory had announced that the solar system now had nine planets, and there could be no argument about that. No matter that most astronomical textbooks written a decade before Lowell was born had stated that there were then already 11 known planets.

It was the addition of Neptune in 1846 and the growing number of discoveries of small bodies between Mars and Jupiter that prompted the astronomical community to count just eight bodies as "planets" and to relegate the lesser bodies to the status of "minor planets" (kleine Planeten, petites planètes, etc.) or "asteroids." Although the term asteroid ("star like") had been coined by William Herschel, it had rarely been used outside the United States, perhaps because, as the discoverer of the substantially larger planet Uranus, Herschel had deliberately intended to convey a somewhat derogatory meaning.

Although in 1930 few astronomers doubted that the young Clyde Tombaugh (who at the time received very little credit for his single-handed and tremendously laborious search) had come across a particularly interesting object, it did not help that the Lowell Observatory provided nothing in terms of quantitative information about the new body apart from a rough estimate of its sky position on the day before their grandiose announcement. The first real evidence came from George(s) van Biesbroeck, whose measurements from photographs obtained at the Yerkes Observatory three and four days later, and published March 20, 1930, on Harvard Announcement Card 112, suggested — but did not by themselves prove — that the new object might be located beyond Neptune.

Confirmation came from the orbital computations by Ernest C. Bower and Fred L. Whipple, graduate students of the University of California at Berkeley and members of what was then the world's leading school for the computation of orbits. On the basis of Van Biesbroeck's data and a three-week series of observations obtained at the Lick Observatory by F. W. Meyer, Bower and Whipple showed (Harvard Announcement Card 118, April 7, 1930) that the new body was some 41 AU from the Earth in an orbit inclined at 17° to the ecliptic with a well-defined nodal direction. Since the orbital eccentricity was completely indeterminate, whether the body was or was not a bona fide transneptunian body was idle speculation, although Bower and Whipple were able definitively to state that, even if the orbit were parabolic, the perihelion distance could not be less than 17 AU.

Finally, a week after the publication of the Bower-Whipple conclusions, the Lowell group published its own orbital calculation on Harvard Announcement Card 121 (April 14, 1930). This was based on just three observations at monthly intervals and although there was a warning that "considerable revision . . . is not unexpected," the Lowell report indicated specific values of 0.909 for the orbital eccentricity and more than 3000 yr for the orbital period.

Since the press had been eagerly awaiting another statement from the Lowell Observatory, they asked Armin O. Leuschner, director of the "Students' Observatory" that hosted Bower and Whipple, for a comment. Leuschner had been impatient over the Lowell group's persistent failure to support its claims and irritated by its public relations success. In the *New York Times* of April 14, 1930, under the subhead "Lowell Observatory Estimates Put Trans-Neptunian Object in Asteroid or Comet Class," Leuschner made the most of his opportunity to speak out: "The Lowell result confirms the possible high eccentricity announced by us on April 5. Among the possibilities are a large asteroid greatly disturbed in its orbit by close approach to a major planet such as Jupiter, or it may be one of many long-period planetary objects yet to be discovered, or a bright cometary object." Then came his coup de grâce: "I have frequently referred to the close orbital and physical relationship of minor planets and comets. High eccentricity and small mass would seem to eliminate object as being planet X predicted by Lowell, and singly an unexpected discovery, nevertheless of highest astronomical importance and interest on account of the great distance of the object in the solar system at discovery."

In fact, authorities such as *Campbell* (e.g., 1916, 1919), *Aitken* (e.g., 1926), and *Leuschner* (e.g., 1927) had been speculating for many years about the possibility of transneptunian planets and the orbital distribution of small bodies in the outer planetary system (cf. *Leuschner,* 1932; *Öpik,* 1932), and had frequently considered comets in general to represent material that had been left over on the outskirts of the solar system beyond the orbit of Neptune. This suggests that these authors may have contemplated the existence of an entity similar to that which is nowadays variously called the Kuiper belt, the Edgeworth-Kuiper belt, or the transneptunian belt. Indeed, *Beekman* (1999) has argued that Leuschner ". . . suggested that Pluto 'could be the first of a large group of such objects'," continuing " . . . in view of its size, Pluto as a comet would of course be exceptional, but in the asteroid belt — between the orbits of Mars and Jupiter — did one not find among the large ensemble of dwarfs also a few giants, such as Ceres, Pallas and Vesta?" However, in playing down the idea that the object soon to be known as Pluto was the "transneptunian planet" predicted by Percival Lowell, it is clear that Leuschner was merely stressing that there are many long-period planetary or cometary objects yet to be discovered. Thus, especially in view of his remarks about high orbital eccentricity, it seems more likely that he was envisaging a much more extended distribution of transneptunian objects.

In this context, a popular article published by Frederick C. Leonard soon after the discovery of Pluto seems more à propos (*Marsden,* 2000). By the middle of May 1930, recognition of a likely prediscovery observation of Pluto from three years earlier had allowed Andrew C. D. Crommelin (*Circ. Brit. Astr. Assoc., 93*) to conclude that the new object had an orbital eccentricity rather less than 0.3 and a perihelion point just inside the orbit of Neptune, results that were confirmed during the following weeks as further old images were located. By August that year, *Leonard* (1930) could therefore write with some confidence: ". . . Now that a body of the evident dimensions and mass of Pluto has been revealed, is there any reason to suppose that there are not other, probably similarly constituted, members revolving around the Sun outside the orbit of Neptune? . . . As a matter of fact, astronomers have recognized for more than a century that this system is composed successively of the families of the terrestrial planets, the minor planets, and the giant planets. Is it not likely that in Pluto there has come to light the *first* of a *series* of ultra-Neptunian bodies, the remaining members of which still await discovery but which are destined eventually to be detected?"

2. FIRST QUANTITATIVE APPROACHES

2.1. Edgeworth

A more comprehensive approach to the problem was made by the independent Irish astronomer Kenneth E. Edgeworth (*McFarland,* 1996) during the 1930s. After a successful military and civilian career, Edgeworth retired to his family home in Ireland and began developing his ideas on the cosmogony of the solar system. This work, "The Evolution of the Solar System," culminated in a manuscript submitted for publication in 1938 (*McFarland,* 2004), which essentially developed the very old idea [dating back, at least, to Kant's (1755) *Universal Natural History and Theory of the Heavens*] that the formation of planets could be understood as a consequence of the accumulation of numerous smaller bodies, or condensations, in a protoplanetary disk that extended far beyond the known planetary orbits. Edgeworth's manuscript lay in the hands of several publishing houses (e.g., George Allen and Unwin Ltd., Methuen and Co. Ltd.) as early as the spring of 1938. It also reached several leading astronomers of the day. For example, at the suggestion of R. A. Lyttleton, a copy was sent by F. J. M. Stratton to W. J. Luyten, who commented favorably upon Edgeworth's approach to the problem in a personal communication to the latter (*Luyten,* 1938).

His published work (*Edgeworth,* 1943, 1949) appears to have been the first quantitative investigation into the possible existence of a vast number of potential comets in an ecliptic annulus beyond the orbits of Neptune and Pluto. Postulating a primordial disk of gas and small particles orbiting around an already well-developed Sun, he proposed, in what was a very early discussion of the effects of viscous and tidal forces on the dissipation of angular momentum in the protoplanetary disk, that if the system was sufficiently dense to cause it to condense into various subregions, then these would coalesce to form the major planets.

On the outskirts of the system, however, beyond Neptune and Pluto, the density of the disk would be lower and the condensation processes that formed the major planets would have insufficient time to operate fully and form large single planets. Thus, again following ideas that can be traced to Kant's cosmogony, Edgeworth noted that owing to the decrease of density in the outskirts of the nebula and the lower velocities of condensations in this region, the rate of growth of individual bodies would decrease rapidly with increasing heliocentric distance (cf. *Bailey,* 1994).

In this way, Edgeworth calculated that at great distances the condensation processes would produce a system comprising a very large number of relatively small "heaps of gravel" that would survive to the present day. He felt that if these bodies were seen at close quarters they would appear as partially condensed clusters composed of a small nucleus with a concomitant Saturn-like disk (*Edgeworth,* 1961). These bodies would become visible as observable comets if perturbed on to Sun-approaching orbits.

In his unpublished manuscript (*Edgeworth,* 1938), he also made order-of-magnitude calculations of the approximate number and sizes of the potential comets beyond Neptune, first for a total mass in the annulus of $0.33\ M_\oplus$ and then for $0.1\ M_\oplus$. These calculations yielded figures of 200 million and 2000 million objects with individual masses of about $2 \times 10^{-9}\ M_\oplus$ and $5 \times 10^{-11}\ M_\oplus$, respectively, i.e., they would be smaller and more numerous than most of the then-known minor planets in the main asteroid belt. The annulus, Edgeworth reasoned, extended from about 65 AU to perhaps over 260 AU and he felt that these numbers and sizes matched those required to replenish the continual loss of comets (*Edgeworth,* 1938).

From his calculations, Edgeworth concluded that Neptune represented the limiting case for the formation of a single large planet in the outer solar system. Unless there was considerably more mass than seemed reasonable in the transneptunian disk, it would be impossible to form a single large transneptunian planet. The status of Pluto, in Edgeworth's mind, appeared to alternate between that of a planet and that of an escaped satellite of Neptune. Of Pluto, he wrote: "Pluto, the latest addition to our list of members of the solar system, is too small to be classed as a major planet, in spite of its position; it has been suggested that it is an escaped satellite of Neptune's and we shall find in due course that there are good reasons for placing it in that category" (*Edgeworth,* 1938). In making this remark he was presumably referring to the paper of *Lyttleton* (1936) on a possible origin for Pluto. Later, in his book (*Edgeworth,* 1961), he sometimes ranks it among the planets.

Overall, Edgeworth had a remarkably interesting and productive life and many of his astronomical ideas anticipated future developments. Given his "amateur" position, it is difficult to know the extent to which his quantitative analysis would have influenced other key workers in the field, which at the time was in a highly fluid state. Nevertheless, it is clear that he had a firm grasp of the problem and a variety of independent views, and it has been argued (e.g., *Brück,* 1996; *McFarland,* 1996, 2004; *Green,* 1999, 2004) that his work should be given greater credit.

2.2. Kuiper

A second significant contribution to the study of the origin of the solar system came from Gerard P. Kuiper (for a biography, see *Cruikshank,* 1993) in a paper published in a symposium to mark the progress of astrophysics during the half-century since the establishment of the Yerkes Observatory (*Kuiper,* 1951a). Although *Kuiper* (1951b) states that this symposium paper had been submitted for publication in November 1949 and was given limited circulation in February 1950, he evidently had time to include discussion of both *Oort*'s (1950) and *Whipple*'s (1950a,b) seminal papers, published in the first quarter of 1950. In his section entitled "Comets and Unknown Planets," Kuiper considered the fate of a belt of nebular material beyond Neptune and extending as far as Pluto's aphelion distance (i.e., from approximately 38 AU to 50 AU). He assumed that the temperature in this relatively stable region was low enough for water vapor, methane, and ammonia to condense first to form "snowflakes" and then objects a few tens of centimeters across (see also *Kuiper,* 1956). He stated that these "snowballs" would continue to combine even long after the dissipation of the solar nebula, so that after a gigayear, the average size of the bodies would be in the region of 1 km across, with the largest ones perhaps up to 100 km across. If the belt of material had a mass of 5×10^{24} kg, Kuiper estimated that this would agree with *Oort*'s (1950) estimate of $\approx 10^{11}$ members of total mass 10^{24} kg in his giant spheroidal comet reservoir.

Kuiper's work resonated with Whipple's icy conglomerate picture for the cometary nucleus (*Whipple,* 1950a,b), although it was developed apparently quite independently of Whipple's work. Kuiper felt that comets had probably not been formed between Mars and Jupiter, as Oort had speculatively suggested, but postulated instead that many of these "snowballs" could be delivered by Pluto's perturbations first toward Neptune and then by further planetary perturbations, including those of Jupiter, into Oort's "comet trap" (cf. *Öpik,* 1932). This mechanism required Pluto to have a mass in the range $0.1–1.0\ M_\oplus$, which, although later disproved by the discovery of Charon (*Christy and Harrington,* 1978), was widely believed at this time. Kuiper concluded that the comets we see today were sent from the giant cometary cloud into the inner solar system by Oort's mechanism of random perturbations by passing stars, which had resulted in their isotropic distribution of directions of approach. Beyond Pluto's aphelion distance of 50 AU, where its dynamical sweeping would be negligible, Kuiper reintroduced the important idea, dating from the previous generation, that a primordial belt of residual nebular material may still exist, and be populated by comets. Kuiper also considered that the fragility of comets and their tendency to disintegrate into small meteoroids was in accord with this scenario.

3. COMET BELT

3.1. Whipple and a Comet Ring

Although Pluto's intrinsic faintness and measurements by Kuiper of its angular size suggested an object having no more than half the diameter of Earth, attempts to determine its mass from its perturbations on other bodies in the outer planetary system persisted in giving figures as large as 0.9 $M_\oplus$ (*Brouwer,* 1951), even into the 1960s. Concerned that the resulting density was impossibly large, *Whipple* (1964a,b) considered that the perturbations might instead come from a ring of icy cometary bodies, of which Pluto would merely be one member. He found that a ring of material having 10–20 $M_\oplus$ at a solar distance of 40–50 AU was one of a number of nonunique solutions that might fit the observations, and he urged that this be tested by better determinations of the orbits of Uranus, Neptune, and Pluto. Supposing that the comet ring consisted of objects of diameter more than 1 km and albedo 0.07 in a disk 2° thick at heliocentric distance 40 AU, Whipple calculated that, even with a total mass of 100 $M_\oplus$, the surface brightness of the disk would be no brighter than 7th magnitude per square degree and therefore undetectable against the glow of the zodiacal light and the gegenschein. He also remarked that, with an apparent magnitude of 22, an individual body as large as 100 km across would still not be detectable with the instrumentation available at the time.

3.2. Observational Constraints

In an attempt to place more exacting demands on the mass of the Whipple comet ring, *Hamid et al.* (1968) computed the effect of the secular perturbations of such a ring on the orbits of seven known periodic comets with aphelia greater than 30 AU. They found that the strongest test would be provided by Comet 1P/Halley, and that their calculations did not support the existence of a comet belt of more than 0.5 $M_\oplus$ to a distance of 40 AU and of more than 1.3 $M_\oplus$ to 50 AU. Although the computation of cometary orbits is complicated by the effects of nongravitational forces, there was some credence to a result in terms of perturbations of the cometary orbital planes, because these are not obviously affected by such nongravitational effects.

Nevertheless, the apparent existence of unexplained perturbations on the orbital planes of Neptune and Uranus continued to be a worry, and it caused others to conclude that moderately massive unknown planets, as well as comets, remained to be discovered within 100 AU of the Sun (cf. *Brady,* 1972; *Goldreich and Ward,* 1972; *Seidelmann et al.,* 1972), and various suggestions were made to detect such hypothetical material (e.g., *Whipple,* 1975; *Bailey et al.,* 1984). *Bailey* (1976) appears to have been the first to consider the role of stellar occultations as a possible probe of these "invisible" outer solar system bodies, and in later work (*Bailey,* 1983a,b, 1986) noted that a suitable density distribution of comets in a spheroidal distribution could be a source of the unmodeled forces previously attributed to "Planet X" as well as a potential additional source for short-period comets. We note the recent detection of apparent "shadows" caused by distant subkilometer objects occulting the compact X-ray source Scorpius X-1 (*Chang et al.,* 2006; cf. *Jones et al.,* 2006), and similarly, the apparent detection by *Roques et al.* (2006) of distant subkilometer objects at visual wavelengths using the high-speed ULTRACAM camera mounted on the 4.2-m William Herschel Telescope.

Another approach was taken by *Jackson and Killen* (1988). They considered that the far-infrared flux emitted by dust produced during the grinding down of bodies through mutual collisions might be detectable. Although they admitted that the number of free parameters made drawing any conclusions from their models difficult, and no such detection of solar system dust was ever made in data taken by IRAS or COBE, submillimeter observations of cool dust disks around other nearby stars have recently spawned a lively area of research.

Thus, during the 1960s through the mid-1980s many authors had begun to consider different models for a trans-neptunian cometary density distribution (e.g., *Cameron,* 1962; *Whipple,* 1964b; *Safronov,* 1969, 1977; *Mendis,* 1973; *Öpik,* 1973; *Biermann and Michel,* 1978; *Hills,* 1981), and thoughtful reviews of the position up to about 1990 were provided by *Hogg et al.* (1991) and *Tremaine* (1990). Soon after, however, from a careful analysis of data from the Voyager mission, *Standish* (1993) appeared finally to lay Lowell's Planet X to rest. He concluded that there was no evidence for any significant unobserved mass in the outer solar system if correct values were used for the masses and orbital elements of the known planets.

3.3. Jupiter-Family Comets

The problem of the origin of the majority of short-period comets — those with periods less than about 20 yr and often described as "Jupiter-family" comets — had confounded, for a century or more, theoretical predictions based on the classical capture of comets from the near parabolic flux. The key difficulty lay in the efficiency of the capture process, i.e., how many short-period comets would be produced from the observed long-period flux. Analytic work (e.g., *Newton,* 1878) had demonstrated that it was impossible to produce the observed number of short-period comets as a result of single close approaches of objects in nearly parabolic orbits to Jupiter. The introduction of powerful new computational tools during the 1970s, however, increasingly focused attention on the process of gravitational capture of comets into short-period orbits by a more gradual random-walk evolution: either "diffusion" of orbital energy (e.g., *Everhart,* 1972) or a more complex process. The latter would involve the exchange of an object's perihelion and aphelion distances as a result of exceptionally close planetary approaches (*Strömgren,* 1947), leading to the "handing down" of comets in the outer solar system from one planet to another (e.g., *Kazimirchak-Polonskaya,* 1972, 1976; *Vaghi,* 1973; *Everhart,* 1976, 1977).

Everhart's work (e.g., *Everhart,* 1972) had highlighted the important role of the so-called "capture zone" in the dynamical evolution of nearly parabolic orbits to short-period, Jupiter-family types. This showed that the majority of captured short-period comets appeared to originate from a rather narrow region of phase space, i.e., from originally nearly parabolic orbits with initial perihelion distances, q, in the range 4–6 AU and initially low ($i < 9°$) inclinations, the capture probability from all other parts of the (q, i) plane being much smaller. According to Everhart's detailed investigations, the gravitational influence of Jupiter, and to a lesser extent that of Saturn, resulted in the capture to short-period orbits of 0.7% of the original near-parabolic flux within this region by the time they had orbited the Sun 2000 times.

Although Everhart had been careful to state that this was not the only evolutionary picture (and the issue of the number of orbits before dynamical capture had occurred was also an important consideration), an influential paper by *Joss* (1973) provided a rather damning counterargument. Given the low efficiency of the perturbative process demonstrated by Everhart, and the fact that inclinations less than 9° account for only a very small fraction (some 0.6%) of the observed isotropic near-parabolic flux, Joss showed that the predicted steady-state number of short-period comets was still too small. Thus, neither "diffusion" nor capture by a single close approach to Jupiter seemed capable of explaining the observed number of Jupiter-family comets, at least from the observed near-parabolic flux. He concluded simply (and correctly!) that the origin of short-period comets was not then understood.

Another approach was highlighted by *Fernández* (1980). He showed that if the observed Jupiter-family comets originated from a steady-state isotropic nearly parabolic flux, the process was so highly inefficient that it should have led to the loss from the Oort cloud (and the planetary system) of more than 10^{12} long-period comets over the age of the solar system. This was many times more than the total number of comets thought to have been originally present. This led him to consider a new source for the short-period comets, namely the transneptunian belt introduced by Whipple and others, tacitly placing the ring of small icy bodies (comets and planetesimals) between 35 AU and 50 AU from the Sun.

The second key innovation made by Fernández was to estimate the rate of orbital diffusion as a result of random gravitational encounters between the comets and planetesimals. The actual efficiency for scattering the bodies on to Neptune-crossing orbits, so that they could in turn be injected on to short-period orbits by the sequential "handing down" process mentioned above, depends on the mass ($M_{max} \sim 10^{21}$–10^{22} kg) of the largest member of the distribution and the differential mass-distribution index ($\alpha \sim 1.5$–1.9). As we have now learned (*Torbett,* 1989; *Torbett and Smoluchowski,* 1990; *Duncan et al.,* 1995), the orbital evolution of these transneptunian objects is driven both by such close approaches and the long-term chaotic gravitational effects of the outer planets, for example, the e–i excitation mechanisms associated with mean-motion resonances in the outer planetary region. Nevertheless, by postulating the existence of Pluto-sized objects in the transneptunian disk, Fernández made a bold suggestion that has since stood the test of time.

After this pioneering work, Fernández began a series of collaborative projects with W.-H. Ip on the orbital evolution of icy planetesimals in the outer planetary accretion zones. Making use of the statistical method of orbital calculation invented by *Öpik* (1951) and *Arnold* (1965), they explored the injection of such icy planetesimals into the Oort cloud and their subsequent return to the inner solar system as near-parabolic comets (*Fernández and Ip,* 1981, 1983). An unexpected result from their numerical modeling effort concerned the outward migration of Saturn, Uranus, and Neptune, accompanied by the inward migration of Jupiter, during the accretion phase of the two outer planets (*Fernández and Ip,* 1984). This process is driven by the extensive exchange of orbital energy and angular momentum of the widely scattered planetesimals, which have total masses comparable to that of the major planets. As discussed below, such an orbital migration process has formed the theoretical basis (*Malhotra,* 1995) for the trapping mechanism of Pluto and other transneptunian objects in the 2:3 mean-motion resonance with Neptune (the so-called "Plutinos").

3.4. Kuiper Belt

A major departure came not just with the potential to integrate the orbits of thousands of comets for timescales comparable to the age of the solar system, but with the focus on a new question, namely the distribution of the *inclinations* of the short-period comets. Noting that the process of gravitational capture should roughly conserve the orbital inclinations of the captured comets, at least in a statistical sense, *Duncan et al.* (1988) found that capture from an initial nearly isotropic parabolic flux would tend to produce short-period comets with a much broader spread of inclinations than are observed. Setting aside the question of how many orbits would be required for the dynamical capture from long-period orbits to take place (the process would generally take longer for high-inclination retrograde orbits than for low-inclination direct types), they concluded that the generally low inclinations of the majority of "short-period" comets with periods less than 200 yr required a flattened distribution of source orbits. This was contrary to the results of Everhart, who had focused on comets with orbital periods less than a dozen years. In particular, they proposed that the observed short-period comets must be fed from a low-inclination cometary reservoir close to the orbit of Neptune. They proposed naming the region the "Kuiper belt," but Tremaine has since noted that when the paper was written they were unfamiliar with the work of Edgeworth. For a review of the later discussion surrounding the name "Kuiper belt," see *Davies* (2001) and *Fernández* (2005).

In order to reduce the amount of computer time required for these direct integrations of orbital evolution, *Duncan et al.* (1988) had increased the masses of the giant planets by a factor $\mu = 40$ in some cases, arguing that this should not significantly affect the relative proportions of objects captured from initially low vs. high inclinations. Although their results failed to conform with those derived from standard "diffusion" theory (e.g., *Stagg and Bailey,* 1989), subsequent work using the rather smaller planetary mass-enhancement factor $\mu = 10$ (*Quinn et al.,* 1990), as well as complementary simulations based on the Öpik-Arnold computational scheme (*Ip and Fernández,* 1991; but cf. *Bailey,* 1992), appeared to confirm the validity of the approximation. Thus, in spite of later investigations (e.g., *Manara and Valsecchi,* 1992; *Valsecchi and Manara,* 1997) to the effect that even $\mu = 10$ would significantly affect the frequency distribution of orbital energy changes per revolution and so distort the long-term dynamical evolution (cf. *Everhart,* 1979), *Duncan et al.*'s (1988) key result — the need for a flattened initial source distribution to explain the observed low-inclination Jupiter-family comets — became firmly established.

3.5. Prediction of Icy Planetoids

In the wake of these dynamical investigations, and specifically following the suggestion by *Fernández* (1980) that there may exist a significant population of massive transneptunian planetesimals or "planetoids" with masses up to that on the order of Pluto, and the earlier suggestions to the same effect by *Drobyshevski* (e.g., 1978, 1981), the threads were finally drawn together in an influential work by *Stern* (1991). Here, he hypothesized the existence of a population of 1000-km-sized ice dwarfs located in an extended disk-like distribution at heliocentric distances ranging from approximately 30–500 AU. Stern based this proposal on the high axial tilts of Uranus and Neptune (suggestive of collisions), the existence of Neptune's large, retrograde satellite Triton (suggestive of a capture event), and the improbability of forming the Pluto-Charon binary (cf. *McKinnon,* 1984). Stern argued that these characteristics of the outer solar system implied that there was once a large population of 1000-km-sized bodies between approximately 20 and 50 AU and that these objects should have been scattered into what he called the "Kuiper disk" and the Oort cloud (e.g., *Stern,* 1998, 2003). He pointed out that optical and infrared sky surveys offered the capability of detecting, or severely constraining, the presence of such objects out to distances of at least 100 AU.

4. EARLY SEARCHES AND DISCOVERY

4.1. Search Programs

A systematic search for distant minor planets was carried out by Charles Kowal between December 1976 and February 1985. Kowal used the 48-in Schmidt telescope at the Palomar Observatory to record 6400 deg^2 of sky to a limiting magnitude of approximately $m_V = 21$ (*Kowal,* 1989). The plates were searched by blinking in the manner of the Pluto search by Clyde Tombaugh. Due to trailing losses, etc., Kowal estimated that slow-moving objects in his survey were detectable to a limiting magnitude of about 20. Although this survey did result in the discovery of the first Centaur, (2060) Chiron (*Kowal,* 1977, 1979; *Kowal et al.,* 1979), plus several comets and Apollo-Amor planet-crossing asteroids, he did not detect any transneptunian objects (TNOs). Due to the nonuniformity of the survey coverage, which was a function of seasonal weather effects, no detailed statistical analysis of the results was considered feasible.

Another early search for distant slow-moving objects (defined as having an apparent motion less than 10 arcsec h^{-1}) was made by Jane Luu and David Jewitt in 1987 (*Luu and Jewitt,* 1988). They used both the 0.6/0.9-m twin Schmidt telescopes at Kitt Peak National Observatory (KPNO) and Cerro Tololo Inter-American Observatory (CTIO) and the McGraw-Hill 1.3-m telescope at KPNO fitted with a 390 × 584 CCD camera. They searched each of 11 5.5-deg^2 Schmidt fields, covering a total of 297 deg^2 to a limiting magnitude m_V of approximately 20, plus a 0.338-deg^2 field with the CCD camera to a limit of $m_R \simeq 24$. No distant objects were found, but in their analysis they noted that the empirical limits set by the existing surveys were too weak to contradict the hypothesis that the Oort cloud might extend into the planetary region.

In April 1989, *Levison and Duncan* (1990) used the U.S. Naval Observatory 1-m telescope at Flagstaff, Arizona, to image 4.88 deg^2 of sky with a 2048 × 2048 CCD. They then used an automated search program to search for moving objects and visually examined any promising candidates reported by the software. They searched for objects with reflex motions that would place them beyond about 25 AU, but were unable to discover any slow-moving objects to a completeness limit of $m_V = 22.5$.

Another unsuccessful search was made by *Tyson et al.* (1992). They imaged a 40 arcmin^2 area repeatedly over several nights with the CTIO 4-m telescope using relatively short exposures to minimize trailing losses. After normal flat-fielding and cosmic-ray removal, they assembled a single deep exposure by summing all the images and then removed this from each of the individual frames to give a set of residual images. They then co-added these residual images in a grid of reference frames centered on potential outer solar system objects with apparent motions between 1" and 4" per hour. Although their methodology was sound, they failed to detect any objects of $m_R < 25$. Published only as an AAS abstract, these results were being written up in more detail by P. Guhathakurta et al. but the paper was never published, being preempted by the announcement of the discovery of 1992 QB_1.

About the same time Anita and William Cochran carried out a survey using the imaging grism instrument mounted on the 2.7-m telescope of the McDonald Observatory. They observed on part or all of 22 nights between November 14, 1990, and March 25, 1993. *Cochran et al.* (1991) claimed that they would be able to detect what they referred to as "giant comets" at 50 AU if they existed, but no discoveries were ever reported from this program.

4.2. First Discoveries

The first object having an orbit that is completely transneptunian was recorded by Jewitt and Luu using the 2.2-m University of Hawaii telescope on Mauna Kea, Hawaii, on August 30–September 1, 1992. Designated 1992 QB_1, it was reported by *Jewitt and Luu* (1992) on September 14. The same circular presented a calculation by Marsden showing that, as had been the case when Pluto was announced, the orbit was completely indeterminate, the current distance from the Earth being anywhere between 37 AU (for a direct parabolic orbit) and 59 AU (for a retrograde parabolic orbit). The assumption of a direct circular orbit yielded a radius of 41 AU and inclination 2°.

Observations over a four-month arc rendered it likely that 1992 QB_1 was indeed the first discovery of an object in a low-eccentricity orbit entirely well beyond Neptune (*Marsden,* 1992), and with the availability of observations at the 1993 opposition the orbital shape and size could be refined to perihelion distance 41 AU and mean distance 44 AU. The discovery was described in detail by *Jewitt and Luu* (1993a). The object is now numbered (15760).

Another object, 1993 FW, located on the opposite side of the sky but that turned out to have a rather similar orbit (perihelion and mean distances 42 AU and 44 AU, inclination 8°) was reported by *Luu and Jewitt* (1993) on March 29.

There were four further discoveries of distant objects during September 1993. 1993 RO and 1993 RP were found by *Jewitt and Luu* (1993b,c) from Hawaii and 1993 SB and 1993 SC by *Williams et al.* (1993) with the 2.5-m Isaac Newton Telescope at La Palma (see also *Williams et al.,* 1995). Commenting on possible orbits, Marsden remarked in particular that direct circular solutions for all four had radii of 32–36 AU, i.e., much closer to Neptune's distance than had been the case for 1992 QB_1 and 1993 FW. The true nature of the orbits of these last four objects will be discussed in the next section.

5. NEW CLASSES OF TRANSNEPTUNIAN OBJECTS

5.1. Plutinos

Although the existence of objects some 60° from Neptune and for which the assumption of direct, circular orbits placed them only slightly beyond Neptune might have hinted that they were Neptune "Trojans," librating in 1:1 orbital resonance with Neptune, it seemed at least as likely that they were instead relatively near the perihelion points of orbits in the 2:3 resonance, which has a much larger phase space. After all, Pluto itself librates in 2:3 resonance with Neptune, a possibility apparently not even suggested until it was firmly established in 1964 (*Cohen and Hubbard,* 1965).

In May 1994, the availability of followup observations of 1993 SC finally provided an opportunity for the publication (*Marsden,* 1994) of the result that the assumption that this object was near perihelion and in the Neptune 2:3 resonance (mean distance 39 AU) could ensure that it would always be more than 14 AU from Neptune. This was at a time when perihelic orbits having mean distances ranging from 34 AU to more than 44 AU would also reasonably fit the observations. The same possibility was also found to be viable for the three less-well-observed discoveries from September 1993. With the availability of observations from later oppositions, the nature of the orbits of 1993 RO, 1993 SB, and 1993 SC could be confirmed as near-perihelion "Plutinos" — a term introduced by *Jewitt and Luu* (1995, 1996) — and the two *Williams et al.* (1993) objects were numbered (15788) and (15789). For a more detailed account, see *Marsden* (1996).

5.2. Other Resonant Types

More often than not, as the pace of TNO discoveries from 1994 onward increased, the initial assumption of perihelic 2:3 Neptune-resonant motion in appropriate cases turned out to be valid. However, in February 1995 another Luu-Jewitt object, now known as (15836) 1995 DA_2, was found for which a circular orbit solution indicated a radius of 34 AU, but which had a longitude almost 180° from Neptune. Since the perihelic 2:3 assumption in this case would yield a close approach to Neptune when the object was at the same longitude, a perihelic orbit in 1:2 resonance (mean distance 48 AU) was initially assumed instead (*Marsden,* 1995a). When the observations extended for more than a month, however, it seemed that a perihelic 3:4 Neptune-resonant orbit would be more viable (*Marsden,* 1995b), and the correctness of this assumption was proven when observations were made at the next opposition. Also in early 1995, another borderline case having an initial circular solution with radius 37 AU was shown at the second opposition to avoid Neptune by virtue of its being in the 3:5 resonance (*Marsden,* 1995c). This object, (15809) 1994 JS, has perihelion and mean distances of 33 AU and 42 AU.

On the theoretical front, it should be noted that various authors were developing the idea that the structure of the transneptunian region might be rather complicated. *Levison and Duncan* (1993) had carried out integrations of test particles over billion-year timescales and found that these led to complex structures in a process that they described as "gravitational sculpting" of the region. Similarly, *Morbidelli et al.* (1995) had begun to explore the resonant structure of the region and *Malhotra* (1993) was considering that, following the ideas of *Fernández and Ip* (1984) concerning planetary migration, the capture of Pluto into the 2:3 resonance was a consequence of early planetary migration and subsequent dynamical evolution of the outer solar system. *Malhotra* (1995) suggested that, in addition to the 2:3 resonance, TNOs should be found librating in the 1:2 resonance with Neptune, and maybe others such as 3:4, 3:5, etc. She further developed these ideas in *Malhotra* (1996). After a few false alarms, the first confirmed cases of 1:2 libration, namely 1997 SZ_{10} and (20161) 1996 TR_{66}, were recognized in December 1998 (*Marsden,* 1998a,b).

In more recent years, both theory (e.g., *Nesvorný and Roig,* 2000, 2001; *Nesvorný and Dones,* 2002; *Lykawka and Mukai,* 2006) and observations have advanced rapidly, with objects now progressively confirmed to be librating in the 4:7, 4:5, 1:1, 5:9, 2:5, 3:7, and 1:3 resonances with Neptune (see chapter by Gomes et al., but cf. chapter by Gladman et al.). The mean distance (44 AU) corresponding to the 4:7 resonance is close to those of the first modern TNO discoveries 1992 QB_1 and 1993 FW, but the librating cases tend to have significantly smaller perihelion distances (as low as 33 AU) than their nonlibrating neighbors. The 5:9 resonance is nearby, although the single 5:9 librator so far confirmed has a perihelion distance of 40 AU (*Chiang et al.,* 2003).

The 42 AU mean distance of the 3:5 librator (15809) lies near the inner edge of a rather extensive population of objects in low-eccentricity orbits. These are variously termed "classical Kuiper belt objects" (classical KBOs) or (as a word-play on 1992 QB_1) "Cubewanos," first introduced by *Marsden* (1997). Similarly, the mean distance (≃48 AU) of the 1:2 mean-motion resonance lies near the outer edge of this "core" TNO population. Of course, these boundaries for the low-eccentricity population may well owe their origin to secular resonances with Neptune, such as the ν_8. In any case, with the discovery of numerous Cubewanos and a growing number of confirmed mean-motion librators, as well as other objects in a wide range of more-eccentric, higher-inclination orbits, it soon became clear that the whole transneptunian region comprises a complex ensemble of different dynamical types, with some subclasses of orbit possibly having quite different dynamical histories from others.

5.3. Classical Kuiper Belt Objects

The objects comprising the core of the transneptunian population, in what effectively covers the range of the Whipple-Fernández comet belt, represent what some authors have called the "Classical Kuiper" or "Edgeworth-Kuiper" belt. These objects were originally thought to be the principal reservoir for short-period comets, with a total population, for semimajor axes in the range 30–50 AU and diameters greater than 100 km, on the order of 10^5 objects. However, with the provision of increasingly accurate orbits for some objects with multiple oppositions and smaller perihelion distances (and so with the potential to undergo close approaches to Neptune), many were found to be Neptune librators. Thus, at least over relatively short timescales, they are protected against close approaches to Neptune and cannot readily evolve onto short-period orbits.

At the time of this writing, it is not known whether these resonant objects are permanently protected against close approaches with Neptune, or whether they might still represent a significant source of short-period comets. What has become clear, however, is that the core nonresonant population mostly comprises orbits with relatively large perihelion distances and very long dynamical lifetimes (*Duncan et al.,* 1995), and so cannot be the dominant source of short-period comets (e.g., *Emel'yanenko et al.,* 2005), as was originally proposed.

5.4. Scattered Disk Objects and Centaurs

The term *scattered disk* was applied by *Torbett* (1989) to postulated icy objects generally in highly eccentric and substantially inclined orbits with perihelion distances beyond Neptune. These were the planetesimals supposedly scattered by Uranus and Neptune toward the Oort cloud, and Torbett remarked that the survival of this hypothetical disk would depend on the efficiency of stellar perturbations in raising their perihelion distances. Following earlier work by *Fernández and Ip* (1981) and *Duncan et al.* (1987), *Torbett* (1989) concentrated on objects with modest inclinations and perihelia in the range 30–45 AU, with a view to finding unstable regions for the subsequent production of short-period comets as the result of successive interactions with all four giant planets.

Whereas *Levison and Duncan* (1997) had focused on the classical Kuiper belt as the principal source of short-period comets, *Duncan and Levison* (1997) had alternatively shown that the same short-period comet population could equally (or perhaps more plausibly) arise as a result of the evolution of a population of Uranus- and Neptune-scattered planetesimals, which they called "scattered icy objects." These comets, as they were assumed to be, would have been formed close to the major planets coevally with the planetesimals that had led to the formation of these same planets, and were identified simply as residual primordial objects from this region, scattered outward by Uranus and Neptune during the final phases of planetary migration and accretion.

With the discovery of the object (15874) 1996 TL_{66} (*Luu et al.,* 1997), having an orbit with perihelion and mean distances of 35 AU and 83 AU and an inclination of 24°, there was an appreciation that this could be representative of the scattered bodies discussed by *Torbett* (1989) and *Duncan and Levison* (1997). 1996 TL_{66} therefore became recognized as the prototype for a new class of known *scattered* KBOs, or later — following the terminology of *Levison and Duncan* (1997) — the first *scattered Kuiper belt* or *scattered disk objects* (SDOs). The second SDO to be recognized was 1998 XY_{95} (*Marsden,* 1999), with perihelion and mean distances 37 AU and 64 AU, respectively, and inclination 7°.

The term SDO is a little unfortunate, because it has never been clear whether it is also applicable to high-eccentricity objects with perihelia that are *inside* the orbit of Neptune — the planet-crossing Centaurs — or indeed whether some of the objects with large perihelion distances and/or large eccentricity are scattered at all. If the term is applied to the Centaurs, should there be an arbitrary lower limit of 25 AU on the perihelion distance of SDOs (cf. *Morbidelli et al.,* 2004a), or should orbits with substantially smaller perihelion distances also be included, for example, (29981) 1999 TD_{10} [perihelion and mean distances 12 AU and 95 AU and inclination 6°; see *Williams* (1999)], and the exceptional object (127546) 2002 XU_{93}, with its record inclination of 78°?

In principle, as noted by *Horner et al.* (2003) and *Emel'yanenko et al.* (2004), there is no clear dynamical distinction between Centaurs and SDOs, as they overlap in space and on long timescales their respective orbital elements can vary over a wide range, evolving from one class to the other. Thus, the Minor Planet Center has for some years presented the orbits of both classes of object on the same web page. In general, a purely dynamical classification scheme should avoid, if possible, drawing arbitrary lines between objects that are on dynamically similar orbits, and implying (or depending upon) information about an individual object's origin, as in the phrase "scattered disk object," until the origin and evolution of the whole solar system is much better understood.

In current parlance, Centaurs are usually regarded as planet-crossing objects moving within the range of the giant planets and SDOs as objects on Neptune-approaching orbits with much longer orbital periods. However, even the second Centaur to be discovered (in 1992), namely (5145) Pholus, with perihelion and mean distances of 9 AU and 20 AU respectively, has an aphelion beyond Neptune and so periodically enters the transneptunian region. As soon as one includes the results of long-term numerical integrations of their orbits (e.g., *Hahn and Bailey,* 1990; *Horner et al.,* 2003, 2004) the essential equivalence of the two classes of object can hardly be avoided, demonstrating that Centaurs and SDOs merely represent different phases of evolution of the same underlying "Centaur" population.

A further important consideration is the maximum perihelion distance within which a TNO may be considered as "scattered" by Neptune or coming under its dynamical influence. Although *Torbett* (1989) had suggested 45 AU, the scattered disk produced in *Duncan and Levison*'s (1997) 4-G.y. integrations had perihelia out to about 40 AU. More recent computations (e.g., *Emel'yanenko et al.,* 2003) have suggested that 38 AU may be a more realistic figure, but in practice there will not be a perfectly sharp boundary: The effects of mean-motion and secular resonances, not to mention the long-term effects of small galactic perturbations, especially on orbits of relatively large semimajor axes, all have significant effects on the objects' long-term evolution (*Emel'yanenko,* 1999; *Mazeeva and Emel'yanenko,* 2002).

Transneptunian objects with perihelia somewhat above 38 AU that otherwise have similar dynamical characteristics to SDOs are sometimes termed *outer* TNOs or *extended* SDOs (*Gladman et al.,* 2002; *Emel'yanenko et al.,* 2003; *Morbidelli et al.,* 2004b), and represent another new population of objects. Their intrinsic number is at least 10 times as many as that in both the classical Kuiper belt and the scattered disk (*Gladman,* 2005). The largest such object so far known (albeit possibly a "borderline" SDO) is (136199) Eris (formerly 2003 UB_{313}) (*Brown et al.,* 2005). It was discovered near the aphelion point of its orbit, and has perihelion and mean distances of 38 AU and 68 AU, and inclination 44°, and is notable also for being somewhat larger than Pluto. Other objects in this new class of outer TNOs (*Gladman et al.,* 2002; *Emel'yanenko et al.,* 2003), which represent either an extended "disk" population or a class of objects merging into the inner Oort cloud, are 2000 CR_{105}, with perihelion distance 44 AU, and (90377) Sedna = 2003 VB_{12}, which is widely regarded as occupying part of the inner Oort cloud (*Brown et al.,* 2004). It has a perihelion distance of 76 AU, an orbital period of around 12,000 yr, and an inclination of 12°.

5.5. More Recent Discoveries

In recent years new discoveries have added further complexity to this already complicated picture. For example, although 90% of the currently known classical Kuiper belt objects have orbital inclinations under 15°, a few objects, including the largest known member, (136472) 2005 FY_9 (*Brown et al.,* 2005), have inclinations around 30°, and there is one (2004 DG_{77}) confirmed at inclination 48°. Similarly, with a perihelion distance of 35 AU, (136108) 2003 EL_{61}, the third of the large TNOs reported in mid-2005 (*Brown et al.,* 2005), qualifies more as an outer TNO or as a borderline Centaur/SDO than as a classical Kuiper belt object. Its inclination (28°) is again somewhat high for the "classical" Kuiper belt, although its mean distance of 43 AU and relatively low eccentricity is arguably in the classical range.

The inclinations of the Plutinos, now numbering approximately 100 objects from among the ~650 TNOs with reliable orbit determinations, also range up to around 30° (with 2005 TV_{189} having the largest value, 34°). However, the Plutinos have a much broader inclination distribution, with less than 25% of the objects having inclinations less than 15°.

The 4:5 resonance is of course somewhat inward of the 3:4 resonance and involves low-eccentricity orbits with semimajor axes around 35 AU. It seems rather unlikely that objects will be found at the 5:6 and higher first-order resonances, as the sequence reaches its limit with the much stronger 1:1 "Trojan" case, of which the first definite example found was 2001 QR_{322} (*Marsden,* 2003; *Chiang et al.,* 2003). At the time of this writing, a total of four Neptune Trojans have been identified, all librating about the leading Lagrangian point L4 (*Sheppard and Trujillo,* 2006).

The most recently recognized populated mean-motion resonances with Neptune, namely the 3:7, 2:5, and 1:3, are beyond the 1:2 resonance, lying near mean distances 53, 55, and 62 AU. Since these librators have perihelion distances around 32–33 AU, they are at first glance indistinguishable from Centaurs, especially as a principal dynamical characteristic of Centaurs is their tendency between episodes of strong planetary perturbations to have semimajor axes close to one or another mean-motion resonance with a controlling planet. Although there is only one confirmed librator at each of the 3:7 and 1:3 resonances — (95625) 2002 GX_{32} = 1994 JV and (136120) 2003 LG_7 (*Wasserman and Marsden,* 2004; *Marsden,* 2005) — the 2:5 resonance (*Chiang et al.,* 2003) is remarkable in that it has more than a dozen well-established librators. Also well beyond the 1:2 resonance there is the exceptional low-eccentricity object 2004 XR_{190}, with perihelion and mean distances 51 AU and 57 AU, close to the 3:8 resonance, and inclination as high as 47° (*Allen et al.,* 2006).

6. CONCLUSIONS

This review of the development of ideas concerning the transneptunian region has brought us from a discussion of the discovery of Pluto through early theories of the structure and evolution of the protoplanetary disk and the origin of short-period comets, to the dynamical links between genuinely *trans*neptunian objects and Centaurs on the one hand, and comets in both the inner and outer Oort cloud on the other. The subject has important implications not just for the origin of the solar system and the formation of the outer planets, but also for understanding the evolution of the inner solar system and the development of life on Earth, for example, through the effects of large comets that can evolve onto Earth-crossing orbits from this outer region (*Bailey et al.,* 1994).

It has taken 75 years since the discovery of Pluto for astronomers to come to grips with some of the dynamical complexity of this outer part of the solar system. This is a period comparable to the century between the discovery of the first few main-belt minor planets and the development of a coherent understanding of the whole region between Mars and Jupiter. In an interesting historical "resonance" with our understanding of the main-belt population, the 2006 International Astronomical Union (IAU) General Assembly in Prague attempted to construct a formal definition of a planet. After much discussion, there was overwhelming support from those present for a motion to restrict the definition of the solar system's "planets" to the eight bodies known both to be in hydrostatic equilibrium and dynamically to dominate their regions of space. Since these eight are not the only solar system bodies in hydrostatic equilibrium, the IAU also agreed to classify as "dwarf planets" other such bodies that do not dynamically dominate their local regions. These "dwarf planets" are numbered in the general catalog of noncometary "small solar system bodies" that have the most reliable orbit determinations and currently include (1) Ceres, the largest of the bodies in the region between Mars and Jupiter, as well as (134340) Pluto and (136199) Eris.

Acknowledgments. We thank many colleagues for discussions. We thank the two referees for their comments, which were carefully considered. Many of their suggestions have been incorporated into the final manuscript. Astronomy at Armagh Observatory is supported by the Northern Ireland Department of Culture, Arts and Leisure. The work of W.-H.I. presented here was supported by grant NSC 94-2112- M-008-033.

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