Transneptunian Binaries

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Abstract.
The discovery of binaries among the population of transneptunian objects is a landmark advance in the study of this remote region of the solar system. Determination of binary orbits will enable direct determination of system masses, fundamental for determination of density, internal structure, and bulk composition. The mere existence of binaries with the observed separations and apparent masses constrains models of planetary formation.

Keywords: Kuiper Belt, binaries

1. The Value of Binaries in Astronomy

From at least the time of Ptolemy ($\sim$200 AD) astronomers have known that some stars appear to be doubles. The first known record of a telescopic observation of an actual binary star was the 1617 observation of $\zeta\ UMa$, Mizar, by Galileo's student Benedetto Castelli (Fedele 1949), although, at the time, the true nature of binaries was not yet known. It was Herschel (1803) who first noted relative motion between binaries, notably $\alpha\ Gem$, that appeared to be elliptical, *i.e.*, in agreement with the hypothesis that stars were subject to Newton's gravitational attraction. It was not until 1827 that an orbit for a binary star, $\xi\ UMa$, was determined by Felix Savary at the Ecole Polytechnique (Griffin, 1998).

The value of binaries was immediately obvious to 19th century astronomers; they could be used to determine the masses of stars. Almost a century later Eddington (1924) used the masses of a few dozen stars to develop the mass-luminosity relation which today still stands as a cornerstone of modern astronomy.

2. Discovery of Transneptunian Binaries

A parallel history of transneptunian binaries (TNB) has unfolded on a much more rapid timescale than the discovery and exploitation of stellar binaries, decades instead of centuries. The identification of Charon, Pluto's moon (Christy and Harrington, 1978) marked the first discovery in the solar system of an object where the barycenter resides outside the primary body, a true binary system.

Less than a decade after the detection of 1992 QB_1, the first member of what has come to be called the Kuiper belt, Veillet (2001) announced the discovery of a second transneptunian binary, a companion to 1998 WW_{31}. More discoveries have followed rapidly (Tables I-III) so that by May 2003 a total of ten transneptunian binaries were known.

The power of the discovery of transneptunian binaries is as obvious to planetary astronomers of our era (e.g. Toth 1999) as the value of binary stars was to stellar astronomers in the 19th century. The masses of transneptunian objects (TNO) are fundamental to a physical understanding of these objects. With the possible exception of a flyby of one yet-to-be-discovered object by the New Horizons spacecraft, orbit analysis of binary systems offers the *only* direct means of determining the mass of these distant objects. Once reliable diameters of TNOs are established, either through analysis of optical and thermal photometry, analysis of lightcurves, observation of stellar occultations, or by direct imaging, it will be possible to determine the bulk density and deduce the internal structure of these objects. Because of the potential availability of mass information, it is likely that TNBs will be intensively observed members of the Kuiper belt.

2.1. Charon

The history of the discovery of Charon, Pluto's moon, is well documented in a number of reviews (e.g. Christy 1997). One facet of the discovery is of particular interest: Charon was detectable in observations and photographs taken years before it was discovered, but was not recognized, possibly because early predictions had dismissed the likelihood of finding a satellite around Pluto (Reaves 1997).

After the discovery of Charon, the mass of Pluto, which had been estimated to be as much as 10 Earth masses before discovery, and which had been estimated to be as high as 0.7 Earth masses subsequent to discovery, was finally fixed close to the currently accepted value of 0.00237 Earth masses for the Pluto-Charon system (Marcialis 1997).

2.2. 1998 WW_{31}

The companion to 1998 WW_{31} was first seen in an image obtained with the CFHT on 20 December 2000 as part of a long-term program to obtain astrometric data and color photometry of TNOs (Veillet et al. 2002). Interestingly, after its discovery, the binary was identified in images obtained as early as November 1998. Possibly, as in the case of

Charon, erroneous preconceptions within the community delayed the discovery of this and other binary TNOs.

Because of rapid followup with the Hubble Space Telescope (HST) and ground-based observations, 1998 WW_{31} was the first Kuiper Belt object, excepting Pluto, to have its mass directly measured. Using a total of 7 HST orbits obtained from July 2001 - Feb 2002, as well as about a dozen lower-precision ground-based observations from November 1998 to September 2001, the semimajor axis was determined to an estimated precision of $\pm 4\%$. A semimajor axis of 22,300$\pm$ 800 km and a period of 574$\pm$ 10 $days$ yields a system mass of $2.67 \pm 0.38 \times 10^{18}$ kg, approximately 5,500 times less than the mass of the Pluto/Charon system. An additional 8 orbits of HST time have since been exposed and will be used to further refine the orbit.

2.3. 2001 QT_{297}

As documented in Table II, four of the TNOs discovered by the Deep Ecliptic Survey team (Millis et al. 1999, 2000, 2001; Wasserman et al. 2001) have later been found to be binaries. An important aspect of the DES has been the systematic followup of objects discovered so that objects with unreliable orbits are not lost. As part of this effort, observations of 2001 QT_{297} were made on 11-12 October 2001 with the Magellan 6.5-m telescope in 0.45 arcsec seeing. Elliot (2001) reported that these observations revealed a second component 0.55 magnitudes fainter than the primary and separated by 0.6 arcsec.

2001 QT_{297} has been extensively observed in subsequent observations at Magellan, sufficient for a preliminary analysis of the orbit and a mass determination. Details are reported by Osip et al. (2003).

2.4. 2001 QW_{322}

Perhaps the most unusual system discovered so far is 2001 QW_{322} (Kavelaars et al. 2001b). First identified in images obtained with the CFHT on 24 August 2001, the system is composed of two equal magnitude components separated by a whopping 4 arcsec. Reporting on observations from 2002, Burns et al. (2002) note "little relative change in position since the 2001 opposition" which contrasts with the earlier statement in the discovery announcement that the objects may have been drifting slowly apart. A lingering question with this object is whether or not it is a bound system, though if the semimajor axis is comparable to the projected separation, the object is well within the Hill radius for plausible ranges of albedo and density.

2.5. 1999 TC_{36} AND 1998 SM_{165}

At least one dedicated search for TNO binaries was underway at the time of the discovery of 1998 WW_{31}. M. Brown unsuccessfully searched for satellites around three bright TNOs, 1996 TL_{66}, 1996 TP_{66}, and 1996 TO_{66} from August 2000 to January 2001 with HST's STIS spectrograph used in imaging mode. As stated in the abstract of HST proposal 8258, the author expected to find satellites close to the primaries: "Collisionally formed satellites analogous to Charon should be at distances of only $\sim$0.2 arcseconds".

A followup program, HST proposal 9110, used the STIS to observe 25 objects, each on two separate epochs. Again, the target list included some of the brightest known TNOs. Two close binaries were indeed identified in observations obtained on 8 and 9 December 2001 (Trujillo and Brown 2002) and 22 and 28 December 2001 (Brown and Trujillo 2002). It is worth noting that in both cases, the magnitude difference between the primary and secondary is approximately 2 magnitudes, larger than other known TNO binaries except for Pluto-Charon.

2.6. 1997 CQ_{29}, 2000 CF_{105}, 2001 QC_{298}, AND 1999 RZ_{253}

Two large HST snapshot programs, proposals 9060 and 9386, with optical and near-infrared photometry of TNOs as the primary goals, have been carried out with the WFPC2 and NICMOS cameras. An important secondary objective of these investigations was the search for binary companions, none of which were known at the time the proposal was submitted. A total of 122 unique TNOs have been observed in these two programs. Five binary systems have been detected, four of them new (Noll et al. 2002a, 2002b, 2002d, 2003).

All four new objects have been observed at multiple epochs with HST. Two of the objects are identifiable in only one of two observed epochs. 1999 RZ_{253} was first detected with NICMOS as part of an infrared photometry program (Noll et al. 2003). Reexamination of data obtained November 2001 as part of proposal 9110 shows elongation in those images consistent with a marginally resolved binary. In the NICMOS data, taken in April 2003, the binary companion is obvious and is cleanly separated from the primary. The binary companion to 2001 QC_{298} had the smallest separation of any binary to date at the time of its identification, only 0.15 arcsec (Noll et al. 2002d). In a second epoch observation taken April 2003, the binary companion is not resolved. In both cases the non-detections indicate that the binary orbit has a sizeable eccentricity and/or an orbit plane that is close to edge on. Given the large eccentricities already observed in other binaries (Table III) and the statistical likelihood of finding an object with a low-inclination orbit plane, both are possible explanations.

3. Orbits

Determination of orbits from relative astrometric positions requires a straightforward application of Kepler's third law

$$m_1 + m_2 = \frac{4\pi^2 a^3}{GP^2}$$

The critical derived quantity, $m_1 + m_2$, depends on the cube of the semi-major axis, a, and the square of the period, P, both of which are derived from positional information. The accuracy of the determination of both quantities is a function not only of the astrometric precision, but also the sampling interval and the number of samples.

In an ideal case where observations are made exactly at both pericenter and apocenter, the uncertainty of the derived semimajor axis is simply root two times the centroiding precision. For observations with Hubble, centroids can be measured at a few milliarcsecond (mas) precision. With typical binary separations of 250 to 500 mas, it is possible to determine the semimajor axis, a, to an accuracy of $\sim$2% which translates to $\sim$10% uncertainty in mass.

In practice, however, many complications are likely to arise in the determination of a. It is becoming increasingly evident that a number of TNBs have highly eccentric orbits. When coupled with the small observed separations, a substantial fraction of objects may be unresolved at pericenter, even by HST. Even when the pair is resolvable throughout its orbit, it is extremely unlikely that observations can be made exactly at pericenter and apocenter when the orbit is completely unknown *a priori*. In that case, it is necessary to determine the orbit with more randomly spaced observations. The unknown inclination of the orbit plane and the orbital eccentricity then become additional parameters that must be fit.

The period is generally easier to measure, given observations with a sufficient baseline, up to years in some cases. However, even in the case of 1998 WW_{31}, the best observed TNB so far, the uncertainty in the period is $\pm$2%. Clearly, substantial observational effort will need to be expended to achieve mass determinations accurate at the 10% level.

4. Colors and Lightcurves

One of the most notable aspects of TNOs is the large spectral diversity that has been found, mostly as measured by broad-band colors (e.g. Boehnhardt et al. 2003, Dourresoundiram et al. 2003, Stephens et al. 2003). Optical and near-infrared colors of individual components of binary systems can be measured separately. If binaries are coeval and primordial, they can be assumed to have formed in nearly identical physical environments, and therefore, be of similar bulk composition. In that case, color would trace the collisional histories of each component. If, however, radial mixing in the Kuiper belt is important and takes place before the formation of binaries, this argument is weakened. Given the large uncertainties in the dynamical history of the Kuiper belt and in the formation of binaries, an empirical approach to evaluating the information content of color in binaries is the most practical way to proceed.

A complicating factor that must be considered in any photometric measurement of binary systems is the possibility that one or both components will have individual lightcurves. Because of the large separation of TNBs discovered so far, tidally locked systems, like Pluto and Charon, are unlikely. Osip et al. (2003) report a measured lightcurve in the secondary of 2001 QT_{297}. Noll et al. (2002e) report a large change in the measured brightness of the primary of 1997 CQ_{29} at one of four epochs. Romanishin et al. (2001) report a 0.56 mag lightcurve with a period of 7.98 hours (assuming a shape-induced lightcurve) for 1998 SM_{165}. Since the secondary in this system is 2 mags fainter and the minimum orbital period for the system is $P > 32$ days, the observed variation must be due to rotation of the primary. In systems with similar sized components, lightcurves of sufficient amplitude may confuse the identification of a "primary".

5. Mutual Events and Stellar Occultations

Every TNB has two mutual event seasons during its $\sim$300 year orbit around the Sun. However, for binaries with long orbital periods, observability from the Earth requires alignment of both components of the binary at the time the line of sight from the Earth lies in the orbit plane. For 100 km diameter binary components separated by 10,000 km the mutual event season is approximately one month. Nevertheless, with the growing number of TNBs it becomes increasingly likely that a mutual event will be observable in the foreseeable future.

An important factor complicating the possible utility of mutual events is the intrinsic faintness of TNBs. The brightest TNB primary is 1999 TC_{36} with a V magnitude of V$\sim$ 20, while the faintest is 2001 QW_{322} with V$\sim$ 24. Large optical and infrared telescopes will be required in order to achieve sufficient time resolution during mutual events. Assuming that such facilities are available, it can be expected that observations of mutual events will improve knowledge of orbits, diameters, and possibly even surface albedo distributions, paralleling the results from the series of Pluto-Charon mutual events (e.g. Binzel and Hubbard, 1997).

Occultations are another means of obtaining information about the diameters and possible atmospheres of distant bodies. A search program for observable events is described by Elliot and Kern (2003).

6. Frequency of Binaries

Data from five observing programs using HST have searched for binary companions yielding the discovery of 6 of the 9 known TNBs, excluding Pluto. These observations are the best source of relatively homogenous data from which statistics on the frequency of binaries can be inferred.

The two programs by K. Noll and colleagues have observed 122 unique TNOs as part of two large snapshot surveys using WFPC2 and NICMOS (Noll et al. 2002e). In both, the sensitivity to binaries is comparable; binary separations of $s \geq 0.15$ arcsec and magnitude differences of $\Delta m \leq 1$ mag are approximate detection limits. Five TNBs have been observed in these two programs, four for the first time. The fifth, 1998 WW_{31}, was included in the target list before it was known to be binary, and would have been discovered with HST had it not been found earlier on the ground. This rate of discovery yields a binary frequency of $4 \pm 2\%$.

The two programs led by M. Brown observed a total of 29 TNOs with the STIS clear filter and resulted in the discovery of two new binaries. The detection limits in these two programs are more sensitive, $s \geq 0.1$ arcsec and $\Delta m \leq 2.5$ mag. The binary rate inferred from these observations is $7 \pm 5\%$, statistically indistinguishable from the larger WFPC2 and NICMOS survey.

The non-detection of binary companions around four TNOs in deep WFPC2 observations taken by A. Fitzsimmons and colleagues (HST proposal 6521) could, in principle, address the possible existence of smaller secondaries missed in shallower surveys. However, the small target sample does not allow for a meaningful statistical conclusion.

Because of the high eccentricity and inclinations of some TNB orbits, some will be observable by HST only during portions of their orbits, as is already demonstrated in the examples of 2001 QC_{298} and 1999 RZ_{253} noted above. Thus, the binary frequencies calculated above are clearly lower limits, even if we disregard the possible existence of a population of more tightly bound systems and/or pairs with larger magnitude differences.

It is interesting to ask other statistically-based questions about TNBs. Are there any trends with dynamical properties that might result from differing efficiencies of formation and destruction mechanisms as a function of orbital dynamics? Of the ten known TNBs, three are resonant objects and the remaining seven are non-resonant (Table II). However, because of the heterogeneity of TNO observations, it is impossible to say more than the existence of binaries in both resonant and non-resonant populations is demonstrated. Limiting the query to a more uniform sample, the targets observed by HST, allows more detailed questions to be asked. Of the 122 unique targets observed in HST proposals 9060 and 9386 about 80% have been assigned to a dynamical class. Of these, about 2/3 are non-resonant TNOs with the remainder split between resonant objects and scattered disk objects. All 5 of the TNBs observed in these two programs have been non-resonant TNOs, a result that might suggest binaries are more common among the classical objects. However, both binaries detected by Brown and colleagues in proposals 8258 and 9110 are resonant objects. Fewer than one-third of their 29 targets were resonant. Thus it seems that small number statistics prevent strong conclusions at this time, though the question will remain interesting until a significantly larger population of binaries is known. Within a dynamical class it is also interesting to ask whether the orbital inclination and eccentricities of binaries are distributed over a range comparable to the class. Table II shows a significant range in these two quantities for TNBs; if there are any trends to be found, the current data are insufficient to reveal them.

7. Origin and Destruction of Binaries

One of the most notable features of TNBs compared to the binaries recently found in the main asteroid belt and among near-Earth asteroids (see review by Merline et al. 2002) is the wide separation and small diameter ratio of TNBs compared to these other two classes. While superficially similar in some ways, it seems likely that different formation mechanisms may be at work in each population (Burns, 2002).

Three distinct formation scenarios for TNBs have been advanced. A model proposed by Weidenschilling (2002) relies on collision and capture in the presence of a third body to form loosely bound pairs. For this scheme to work, the density of the Kuiper belt must have been at least 100 times greater than the currently observed belt, possibly consistent with the projected mass of the protosolar disk. Goldreich et al. (2002) offer an alternative model wherein capture takes place during close encounters as the result of dynamical friction in the presence of surrounding small bodies. Funato et al. (2003) offer a third option in which primordial binaries with large mass ratios and tight orbits formed through collision go through an exchange reaction to produce binaries with small mass ratios in large, eccentric orbits.

Each of these three scenarios predict unique observable consequences for the binary population. The Weidenschilling (2002) model favors the production of wide binaries, up to 1/3 the Hill radius. Goldreich et al. (2002) are able to reproduce a population where ~5% have binaries with separations of 0.2 arcsec or more and an increasing binary fraction at smaller separations. The Funato et al. (2003) model predicts wide binaries with almost exclusively large eccentricities of $e > 0.8$. These predictions can be tested by the discovery and characterization of a larger sample of TNBs.

At the distance from the Sun of a typical TNO, the Hill radius, $r_H = (\mu/3)^{1/3}R$ is approximately 10^4 times the radius of a TNO primary assuming it has a density comparable to the Sun's, 1.4 $g\ cm^{-3}$. Even the most widely separated TNB, 2001 QW_{322}, has $a/r \approx 1500$ and is thus a bound system stable against perturbations from the Sun and planets. Close encounters and collisions with other TNOs, however, are able to disrupt weakly bound binaries and some have mean lifetimes significantly shorter than the age of the solar system (Petit & Mousis 2003). This loss mechanism implies a larger primordial population of binaries with only a remnant population surviving to the present time.

8. Future Prospects

The discovery of transneptunian binaries is a major step forward in the study of the Kuiper belt. The prospect of directly determining the mass of a significant number of TNOs opens the way for advances in understanding the current mass of the Kuiper belt as a whole, as well as the composition and interior structure of TNOs. The statistical properties of the TNB population can illuminate the formation mechanism of these systems and, possibly, the conditions in the primordial Kuiper belt.

Table I. Observable Properties of TNO Binaries.

Object	sep[1]	H mag[2]	Δmag	Discovery
Pluto	0.9	-0.8	3.2(v)	Christy & Harrington (1978)
1998 WW_{31}	1.2	6.1	0.4(R)	Veillet (2001)
2001 QT_{297}	0.6	5.5	0.55(R)	Elliot (2001)
2001 QW_{322}	4.0	7.8	0.0(R)	Kavelaars et al. (2001)
1999 TC_{36}	0.37	4.9	2.2(c)	Trujillo & Brown (2002)
1998 SM_{165}	0.23	5.8	1.9(c)	Brown & Trujillo (2002)
1997 CQ_{29}	0.33	7.4	0.2(V)	Noll et al. (2002a)
2000 CF_{105}	0.97	8.0	0.9(V)	Noll et al. (2002b)
2001 QC_{298}	0.17	6.0	0.5(J)	Noll et al. (2002d)
1999 RZ_{253}	0.25	5.9	0.0(J)	Noll et al. (2003)

Because of the great benefits of TNBs, it is likely that they will remain a focus of intensive research. Both ground-based and space-based facilities will be required. In particular, facilities with high angular resolution, tens of milliarcseconds or better, will be required to detect objects in tight orbits and/or high contrast systems and to accurately determine orbits. Large synoptic surveys currently planned will discover large numbers of new TNOs and will add to the discovery rate of binaries with wide separations.

Within the next decade, it is possible that hundreds of binary systems in the Kuiper belt will be discovered and exploited. At that time, much of the new knowledge of the basic physical and chemical parameters of the transneptunian frontier will be directly traceable to the existence of these surprising celestial twins.

[1] Separations are the semimajor axis for objects with well-determined orbits, i.e. Pluto and 1998 WW_{31}. All others are the maximum observed separation which, in the limit of a system with an orbital eccentricity of $e = 1$, is $2a$.

[2] H magnitudes (V(1,1,0) for 1997 CQ_{29} and 2000 CF_{105} primaries as measured by HST. For other objects, H magnitudes are taken from the Minor Planet Center and refer to the combined magnitude of an unresolved binary and use undocumented color assumptions.

Table II. Heliocentric Orbital Properties of TNO Primaries.

Object	a	e	i	dynamical class	Reference
Pluto	39.5	0.25	17.1	3:2	Slipher (1930)
1998 WW_{31}	44.8	0.08	6.8	NR	Millis et al. (1999)
2001 QT_{297}	43.8	0.03	2.6	NR	Millis et al. (2001)
2001 QW_{322}	44.1	0.08	4.8	NR	Kavelaars et al. (2001a)
1999 TC_{36}	39.4	0.22	8.4	3:2	Luu et al. (1999)
1998 SM_{165}	47.6	0.37	13.5	5:2	Danzl and Marsden (1999)
1997 CQ_{29}	45.5	0.12	2.9	NR	Chen et al. (1997)
2000 CF_{105}	44.2	0.04	0.5	NR	Millis et al.(2000)
2001 QC_{298}	46.2	0.12	30.6	NR	Wasserman et al. (2001)
1999 RZ_{253}	43.6	0.09	0.6	NR	Trujillo et al. (2000)

Table III. Mutual Orbital Properties of TNO Binaries.

Object	a’	e’	i’	Period (days)	mass (10^{18}kg)	Reference
Pluto	19,600	0	96	6.39	14,600	
1998 WW_{31}	22,300	0.8	42	574	2.7	Veillet et al. (2002)
2001 QT_{297}	30,000	0.25	131	788	3.5	Osip et al. (2003)
2001 QW_{322}	>58,000					
1999 TC_{36}	>5,900					
1998 SM_{165}	>3,300					
1997 CQ_{29}	>4,900	>0.6		320		Griffin (priv. comm. 2003)
2000 CF_{105}	>15,000					
2001 QC_{298}	>2,500					
1999 RZ_{253}	>3,200					

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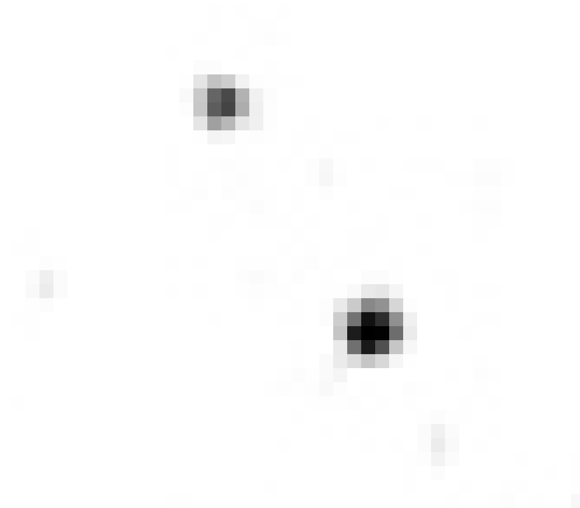

Figure 1. 1998 WW_{31} was the first binary TNO to be discovered since the detection of Charon. This image was taken by the WFPC2 camera on the Hubble Space Telescope on 12 July 2001, just six months after discovery of the object at the Canada-France-Hawaii telescope (Veillet et al. 2002).

References

Binzel, R. P. and W. B. Hubbard. in *Pluto and Charon* ed. S. A. Stern and D. J. Tholen, University of Arizona Press: Tucson, pp. 85-102, 1997.

Boehnhardt, H., et al. *this volume*, 2003.

Burns, J. Science 297, 942-943, 2002.

Burns, J., V. Carruba, and B. Gladman. MPEC 2002-L30, 2002.

Brown, M. E. and C. A. Trujillo. IAUC 7807, 2002.

Chen, J., C. Trujillo, J. Luu, D. Jewitt, J. J. Kavelaars, B. Gladman, and W. Brown. MPEC 1997-J02, 1997.

Christy, J. W. and R. S. Harrington. AJ 83, 1005, 1978.

Christy, J. W. in *Pluto and Charon* ed. S. A. Stern and D. J. Tholen, University of Arizona Press: Tucson, pp. xvii - xxi, 1997.

Danzl, N. and B. G. Marsden MPEC 1999-Y19, 1999.

Doressoundiram, A., et al. *this volume*, 2003.

Eddington, A. S. MNRAS 84, 308-332, 1924.

Elliot, J. L. IAUC 7733, 2001.

Elliot, J. L. and S. D. Kern *this volume*, 2003.

Fedele, U. Coelum 17, 65-69, 1949.

Funato, Y., J. Makino, P. Hut, E. Kokubo, and D. Kinoshita Nature, in press, 2003.

Goldreich, P., Y. Lithwick, and R. Sari. Nature 420, 643-646, 2002.

Griffin, R. F. The Observatory 118, 273-298, 1998.

Herschel, W. Phil. Trans., p.339 1803.

Kavelaars, J. J., J.-M. Petit, B. Gladman, M. Holman, P. Nicholson, C. Dumas, A. W. Harris, and B. G. Marsden MPEC 2001-V34, 2001.

Kavelaars, J. J., J.-M. Petit, B. Gladman, and M. Holman IAUC 7749, 2001.

Luu, J. X., D. C. Jewitt, C. A. Trujillo, D. Tholen, S. Sheppard, E. P. Rubenstein, C. R. Smith, L.-G. Strolger, C. W. Hergenrother, and B. G. Marsden MPEC 1999-Y19, 1999.

Marcialis, R. L. in *Pluto and Charon* ed. S. A. Stern and D. J. Tholen, University of Arizona Press: Tucson, pp. 27-83, 1997.

Merline, W. J., S. J. Weidenschilling, D. D. Durda, J.-L. Margot, P. Pravec, and A. D. Storrs. in *Asteroids III* eds. W. F. Bottke, Jr., A. Cellino, P. Paolicchi, and R. P. Binzel University of Arizona Press: Tucson, pp. 289-312, 2002.

Millis, R. L., M. W. Buie, R. M. Wagner, D. W. Willmarth, P. S. Smith, D. L. Harmer, A. Saha, J. L. Elliot, M. J. Holman, T. Grav, and B. G. Marsden MPEC 1999-B24, 1999.

Millis, R. L., M. W. Buie, R. M. Wagner, J. L. Elliot, D. L. Harmer, D. W. Willmarth, P. S. Smith, A. Saha, S. D. Kern, L. H. Wasserman, and B. G. Marsden MPEC 2000-F02, 2000.

Millis, R. L., L. H. Wasserman, M. W. Buie, E. L. Ryan, S. D. Kern, J. L. Elliot, K. E. Washburn, and B. G. Marsden MPEC 2001-T38, 2001.

Noll, K., D. Stephens, W. Grundy, J. Spencer, R. Millis, M. Buie, D. Cruikshank, S. Tegler, and W. Romanishin. IAUC 7824, 2002a.

Noll, K., D. Stephens, W. Grundy, J. Spencer, R. Millis, M. Buie, D. Cruikshank, S. Tegler, and W. Romanishin. IAUC 7857, 2002b.

Noll, K., D. Stephens, W. Grundy, J. Spencer, R. Millis, M. Buie, D. Cruikshank, S. Tegler, and W. Romanishin. IAUC 7959, 2002c.

Noll, K., D. Stephens, W. Grundy, D. Cruikshank, S. Tegler, and W. Romanishin. IAUC 8034, 2002d.

Noll, K., D. Stephens, W. Grundy, R. Millis, M. Buie, J. Spencer, S. Tegler, and W. Romanishin, and D. Cruikshank. AJ 124, 3424-3429, 2002e.

Noll, K., D. Stephens, W. Grundy, D. Cruikshank, S. Tegler, and W. Romanishin. IAUC 8143, 2003.

Osip, D. J., S. D. Kern, J. L. Elliot *this volume*, 2003.

Petit, J.-M., O. Mousis Icarus, submitted, 2003.

Reaves, G. in *Pluto and Charon* ed. S. A. Stern and D. J. Tholen, University of Arizona Press: Tucson, pp. 3-25, 1997.

Romanishin, W., S. C. Tegler, T. W. Rettig, G. Consolmagno, and B. Botthof DPS meeting abstract 33.0606, 2001.

Slipher, V. Lowell Obs. Observation Circ., March 13, 1930.

Stephens, D., K. S. Noll, W. M. Grundy, R. L. Millis, J. Spencer, M. Buie, S. C. Tegler, W. Romanishin, D. P. Cruikshank *this volume*, 2003.

Toth, I. Icarus 141, 420-425, 1999.

Trujillo, C. A., and M. E. Brown. IAUC 7787, 2002.

L. H. Wasserman, E. L. Ryan, M. W. Buie, Millis, R. L., S. D. Kern, J. L. Elliot, K. E. Washburn, and B. G. Marsden MPEC 2001-T40, 2001.

Veillet, C. IAUC 7610, 2001.

Veillet, C., J. W. Parker, I. Griffin, B. Marsden, A. Doressoundiram, M. Buie, D. J. Tholen, M. Connelley, and M. J. Holman. Nature 416, 711-713, 2002.
Weidenschilling, S. J. Icarus 160, 212-215, 2002.