Missing: a source of short-period comets

Bill Worraker

Astronomers have now discovered more than 700 objects accompanying Pluto in the region of space known as the Kuiper Belt, which lies beyond the orbit of Neptune. These objects have diameters ranging up to 1,000 km or more. The population of bodies they represent is generally believed to be the source of the Jupiter-family comets, the largest group of short-period comets. However the most sensitive searches show that the Kuiper Belt contains far fewer objects than previously estimated. In fact there is a shortfall against theoretical estimates of at least three orders of magnitude in the numbers available to sustain the Jupiter-family comets. The analysis presented here, which considers size differences and fragmentation processes, implies that the currently-estimated Kuiper Belt population cannot sustain the Jupiter family of comets for billions of years as demanded by evolutionists. The data, however, are consistent with a biblical timescale for solar system history in which the Jupiter-family comets may be a decaying population originally released by a major disturbance at the time of the Genesis Flood.

The late northern summer of 1992 saw a significant advance in human understanding of the outer solar system. David Jewitt and Jane Luu, working with a CCD camera attached to the University of Hawaii's 2.24-metre telescope on Mauna Kea, spotted a faint object moving slowly westward in the manner expected for a solar system object orbiting beyond Neptune.[1] The new object, which shone at about magnitude 23, six million times fainter than stars just visible to the naked eye, was given the prosaic designation 1992 QB_1. Each orbit takes over 290 years,[2] and its average distance from the sun is 43.8 AU (1 AU, or Astronomical Unit, is the average sun-Earth distance, about 150 million km). Assuming that its albedo, the reflected fraction of the sunlight which falls on it, is about 0.04 (a typical value for dark asteroids), its estimated diameter is 250 km.[3]

Many more objects orbiting the sun in this region of space, known officially as Transneptunian Objects or TNOs, have now been discovered.[4] The rate of discovery has increased considerably since about 1998, thanks to a greater number of dedicated searches, larger CCD (charge-coupled-device) chips and developments in the supporting software. The largest TNOs found so far are LM_{60}, known as Quaoar (pronounced kwa-o-wah), and 2004 DW, with estimated diameters of about 1,250 km and 1,600 km respectively,[5,6] over half the value for Pluto; these figures are very approximate. One of the Quaoar discovery images is shown in figure 1.

The latest total of recognized TNOs (May 2004) is 789.[7] Figure 2 shows a plot of orbital eccentricity, *e*, against the orbital semi-major axis, *a*, for all known TNOs. Caution is necessary in interpreting this plot, owing to the relatively large uncertainties in *e*, as more than half the objects have only been observed around one opposition.[8] However, the plot has some noteworthy features. Most striking, perhaps, is the cluster around $a \approx 39.4$ AU, with *e* values in excess of 0.06. The corresponding orbital periods are around 247 years, almost exactly 1.5 times Neptune's orbital period. Since Pluto (see figure 2) falls squarely within this group, they are called *Plutinos*. In evolutionary terms they are understood as a group of bodies which have been disturbed by Neptune (hence their relatively high eccentricities) and have thus settled into Neptune's 3:2 *mean-motion resonance*, which is believed to be stable over very long timescales. Other orbital resonances, viz. 4:3, 5:3 and 2:1, have also been recognized in the data,[9] but these are not very obvious in the plot.

Two other groups have also been discerned among the TNOs, namely: (1) *Classical Kuiper Belt Objects* (CKBOs), which have low-eccentricity and generally low-inclination orbits at distances larger than about 42 AU; these are generally believed to be primordial,[9,10] since dynamical simulations suggest that they are unlikely to have been disturbed by Neptune over the alleged evolutionary lifetime of the solar system; and (2) *Scattered Disk Objects*, which have higher eccentricities and inclinations and which are believed to have been ejected from the Uranus-Neptune region by planetary encounters; their orbits are not stable over billions of years, and future encounters with Neptune could possibly send them into the inner solar system.[10] The Minor Planet Center no longer distinguishes between scattered disk objects and Centaurs.[11]

Significance of Transneptunian Objects

What is the significance for creationists of these Transneptunian Objects? Another name for them is Kuiper Belt Objects (KBOs) since they occupy a region of space known as the Kuiper Belt or Edgeworth-Kuiper Belt. Such a region had been postulated in the 1940s by Edgeworth and in 1951 by Kuiper as a possible source of cometary nuclei, complementary to the much larger and more distant Oort cloud postulated by Oort in 1950. Faulkner[12] reviewed the evidence for these proposed sources of comets, noting that direct observational evidence for the existence of the Oort

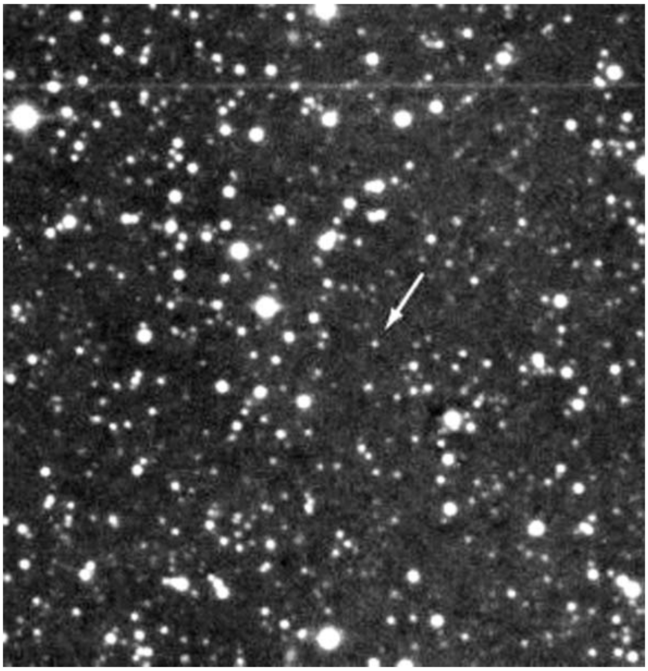

Figure 1. One of the discovery images of LM_{60} or Quaoar (arrowed), which was at about magnitude 19 at the time. From C. Trujillo's webpage at <www.gps.caltech.edu/~chad/quaoar/quaoardisc.gif>.

cloud was still completely lacking. Taking the dividing line between short and long cometary periods to be at 200 years, he noted that the sources of short- and long-period comets must be different since they formed dynamically distinct groups despite having similar compositions.

Short-period comets generally have prograde, low-inclination orbits around the sun, i.e. they orbit in the same direction and roughly in the same plane as the planets. Long-period comets, on the other hand, can orbit in either direction (prograde or retrograde) and with practically any orientation. Moreover, simulations have shown[13] that short-period comets could not have arisen from a spherical distribution of nuclei like the Oort cloud; the Transneptunian region, or Kuiper Belt, fits the bill much better. Hence for several years evolutionists have generally reckoned that long-period comets come from the Oort cloud and short-period comets from the Kuiper Belt. A refinement of this picture is that only *Jupiter-family comets*, i.e. comets with orbits strongly influenced by Jupiter,[14] are directly associated with the Kuiper Belt; there is also a small group of *Halley-family comets* which we are not considering here.[15]

Quantitative assessment

Given the discovery of over 700 TNOs, can we assess *quantitatively* whether the emerging Kuiper Belt could supply Jupiter-family comets for the billions of years demanded by evolutionists? A recent study[16] reports the results of a search for extremely faint TNOs using the Advanced Camera for Surveys (ACS), aboard the Hubble Space Telescope. It also reviews the results of other searches carried out since 1998. In general there is a trade-off between the sky area covered in a search and its depth, i.e. the faintest objects it can detect. Thus at one extreme is a survey covering 1,430 square degrees and reaching magnitude 20.2, while the new survey covered only 0.019 square degrees, but reached magnitude 28.7. Combining the results of all these searches, Bernstein *et al.*[16] draw several statistically-based conclusions about the objects populating the Transneptunian region. They discerned two main dynamical groups, classical Kuiper Belt objects (or CKBOs, as defined above), with an estimated total mass of 0.01 M_E (where M_E is the mass of the earth) and *Excited* objects with a mass totalling perhaps a few times this; the latter group includes Plutinos and scattered disk objects, the common factor being dynamical evidence of interaction with Neptune.

The derived size distributions imply that the largest Excited body should have roughly the mass of Pluto, which is consistent with the view that Pluto is simply a large–probably the largest—Excited TNO.[17] Another significant conclusion is that the CKBO population of objects larger than about 40 km ends sharply at about 50 AU, beyond which there seems to be a gulf of several tens of AU.[18]

According to Bernstein *et al.*,[16] extrapolation of TNO detection rates from brighter surveys predicts that the new survey should have detected ≈85 new objects. In fact it produced just **three**, the faintest at magnitude 28.38±0.05, more than 100 times fainter than 1992 QB_1! Thus there is a major deficit of small TNOs. The deficit is even more striking when the Kuiper Belt is viewed as a source of Jupiter-family comets, since dynamical models of comet precursor populations demand very much higher sky densities of objects which the ACS survey could have detected. In the words of Bernstein *et al.*:

> '... theoretical estimates are wildly inconsistent with the results of our ACS survey. The best-fit observational estimates fall short of the theoretical models by 2 to 4 orders of magnitude.'[16]

This refers to four papers which all model the release of comet nuclei from the Kuiper Belt via encounters with Neptune over evolutionary timescales, but assume different sub populations as the source. Rough estimates of the required and actual sizes of the present-day source populations down to a magnitude limit of 28.5[19] are listed in table 1.

The figures in the last column are based on Bernstein *et al.*'s figure 8, which is reproduced here as figure 3,[16] but assume that the Kuiper Belt covers a sky area of 4,320 square degrees, which is more realistic than the 10^4 square degrees quoted in their paper.[24] Since Plutinos and scattered disk objects are not distinguished in the plot, I have split the totals for Excited TNOs in the same ratio as seen among the known TNOs.[25] Bernstein *et al.* state that the scattered disk model of Duncan and Levison gives the closest match between theory and observation. However, in this model the Classical KBOs are the source of a large disk of scattered objects comprising the Kuiper Belt scattered disk objects,

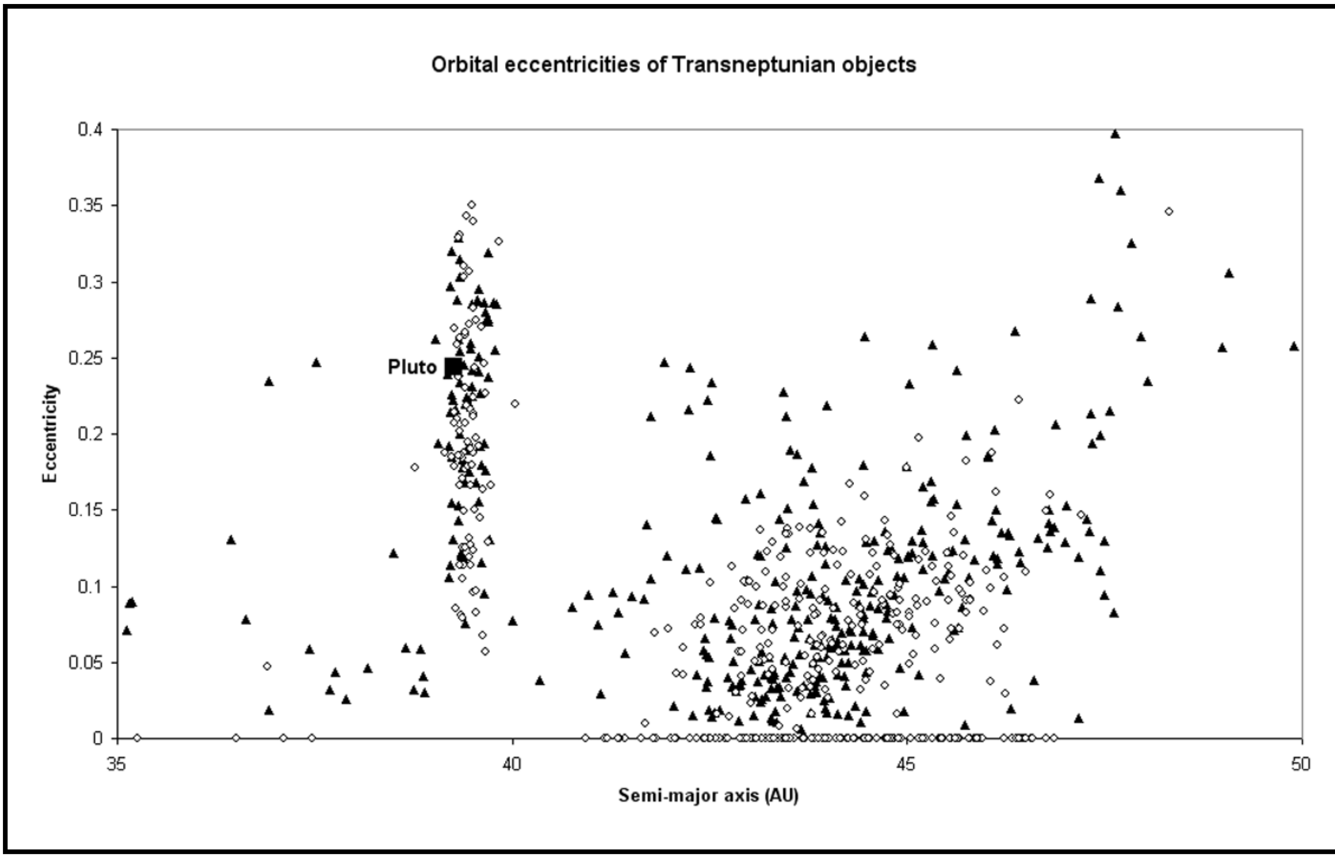

Figure 2. *Orbital eccentricity plotted against the orbital semi-major axis for all currently-known Transneptunian objects. Solid triangles indicate objects which have been observed at more than one opposition, and therefore have relatively well-determined orbits. Open circles indicate objects observed around only one opposition—orbital parameters have larger uncertainties. The large square indicates Pluto. Data taken from the Minor Planet Center list (see ref. 7).*

the Centaurs and the Jupiter-family comets. This requires a present-day Classical KBO population of ~7×10^9, implying a real discrepancy of more than three orders of magnitude. Assuming that Bernstein *et al.* have otherwise correctly compared theory and observation for visible Jupiter-family comets and for TNOs down to a standardized magnitude of 28.5, I conclude that all best-estimate figures for the Kuiper Belt population are 3 to 4 orders of magnitude lower than predicted theoretically.

Questions of time

The lifetime of the Kuiper Belt against the loss of comet nuclei may be assessed in terms of either numbers or mass by comparing its contents against the rate of loss needed to sustain the present-day Jupiter-family comet population. This is difficult because comet nuclei are typically much smaller than TNOs. According to Tancredi *et al.*,[26] the largest Jupiter-family comet is 29P/Schwassmann-Wachmann 1, with an estimated nuclear diameter of 26.4 km. The smallest TNO detected by Bernstein *et al.*, 2003 BH_{91}, has an estimated diameter of 25 km. Thus, extrapolation of the observed Kuiper Belt population down to a diameter of 1 km is needed to bridge the gap.

The population of active, visible Jupiter-family comets has been estimated down to 1.4 km diameter by Fernández *et al.*[27] as about 1,800, though the margin of uncertainty is about 50%. These authors estimate that the additional number down to 1 km diameter, which appears to be the lower limit for a comet nucleus (below which it readily disintegrates), is in the thousands. For subsequent calculation, I will take the total population to be at the low end of their suggested range at 3,000. The destruction rate of the comets due to outgassing during perihelion passage has been estimated by Hughes.[28] His results imply a Jupiter-family lifetime[29] of around 10,000 years, while Levison and Duncan[21] estimate a figure of ~12,000 years. This means that a time-averaged value of 1 comet every 3–4 years is required to maintain the population. If all the new comets result from TNO encounters with Neptune, the loss from the Kuiper Belt is larger than this by a factor of about 3 to account for objects ejected from the solar system,[13,21] resulting in an approximate average loss of 1 TNO every year.

The population figures tabulated above cannot be used directly for a lifetime estimate without somehow accounting for small TNOs. I have extrapolated numerical integrations of the double power law formulae presented by

Table 1. Summary of theoretical predictions compared with best-estimate observed values for the Kuiper Belt sub populations which have been suggested as possible sources of Jupiter-family comets. The figures in the last column are based on a sky area of 4,320 square degrees, which Bernstein (ref. 24) suggests as more realistic than the 10^4 square degrees assumed in Bernstein et al. *(ref. 16).*

Authors	Source population	Numbers required	Estimated actual population (best estimate)
Holman and Wisdom[20]	Classical KBOs	4.5×10^9	8×10^5
Levison and Duncan[21]	Classical KBOs	7×10^9	8×10^5
Duncan and Levison[22]	Scattered disk	1.4×10^8	1.3×10^5
Morbidelli[23]	Plutinos	4.5×10^8	2×10^5

Bernstein *et al.* down to magnitude 35, corresponding to a diameter of 1 km, and then scaled up the results to account for differences between their numerical method (Bayesian statistical analysis) and mine. This gives totals of 2×10^8 for the Classical KBO population and 4×10^5 for the Excited population and implies that Excited TNOs in the 1–20-km size range are very scarce indeed. Dynamical considerations (i.e. orbital characteristics) as well as the modelling studies cited above indicate strongly that the Excited TNOs are the most likely *immediate* precursors of the Jupiter-family comets. However, at the suggested depletion rate of 1 comet per year, the Excited population is clearly inadequate to provide comets for billions of years. This conclusion remains valid in the absence of significant fragmentation even if we allow a generous margin of uncertainty in the data-fitting of Bernstein *et al.* (say by a factor of 100) plus an unprecedented and theoretically unsupported large increase in the number of Excited objects in the extrapolated size range. Furthermore, from the above figures the best-guess estimate for the Classical KBO lifetime is 200 million years, which is also inadequate unless we allow at least a further factor of 10 to cover data-fitting uncertainties.

If we grant that the Classical KBO lifetime might thus stretch to billions of years, could the CKBOs actually provide comets for this length of time, either (i) directly or (ii) by replenishing the Excited population? Option (i) seems improbable because CKBOs on their way to becoming comets will generally pass through a stage in their dynamical evolution which strongly resembles Excited TNOs or Centaurs; in other words they will join the Excited population. To evaluate option (ii), we note that although the size distributions of the two populations both flatten out at the small end, their slopes are significantly different throughout; the Excited population contains more large objects and fewer small objects than the Classical population (see figure 3). Unless significant fragmentation is going on, either in the process of transfer between populations or within the Excited population, we would expect the two populations to have similar size distributions.

This brings us to the major question of **fragmentation**. Estimates by Bernstein *et al.*[16] show that there is sufficient mass in either TNO population to maintain the Jupiter family of comets for tens of billions of years. However, this only alleviates the number problems described above if TNOs are breaking up as a result of collisions with other TNOs or of tidally stressful encounters with Neptune. A generic prediction of accretion/erosion models of planetesimal populations is that the size distribution flattens out below some size. This occurs because large bodies possess sufficient gravity to retain collision fragments, and thus tend to accrete, while smaller bodies do not retain them, and thus erode. The critical size is determined essentially by the relationship between typical encounter velocities and escape velocities, the mechanical strength of the colliding bodies being an important factor. According to Bernstein *et al.*, the critical diameter in the Transneptunian region is of order 100 km. Referring to the extremely shallow slopes observed in the small-end size distributions they state:

> 'This suggests that erosion is very advanced in the Kuiper Belt, with small bodies nearly completely depleted from their original levels, and present-day collisions being insufficient to replenish the supply of small bodies. Alternatively, early accretion may have had a preferred scale, merging all 10 km bodies into 100 km bodies—but completely failing to produce 1,000 km bodies in the CKB, and accreting only 10% or so of the mass into D ≥ 100 km bodies in the Excited population.'[30]

The first sentence here is the most relevant. It seems to rule out the possibility that the Classical KBO population can be supplying the Excited population with small bodies through collisions. To clarify this point, however, we need a figure for the collision rate. Davis and Farinella[31] estimate that about 10 fragments, 1–10 km in size, are produced every year by collisions in the inner Kuiper Belt, with enough of them entering chaotic resonant orbits to maintain the Jupiter family of comets. Davis and Farinella assume a current TNO population of $\approx5\times10^9$ down to 2 km diameter, and remark that this is consistent with '10^{10} comet-sized bodies within 50 AU'. However, current estimates of the Kuiper Belt population are much lower than these values, implying a much lower fragmentation rate. Since the collision rate scales approximately as the square of the population density, the actual collision rate, and the resulting fragmentation rate, will be approximately 1,000 times smaller. This in turn appears to rule out collisions as an effective means of sustaining the Excited TNO population.

The possibility of transfer between TNO populations as a result of encounters with Neptune has already been considered in that the first three studies tabulated above (Holman and Wisdom, Levison and Duncan, Duncan and Levison) all model the transfer of Classical KBOs into the Centaur and Jupiter-family comet populations via an intermediate stage as Excited TNOs. However, since the required parent population was 3 to 4 orders of magnitude too high, we may discount this as a means of replenishing the Excited population unless Neptune frequently induces fragmentation of objects passing close to it. A celebrated example of this effect was the disruption of comet Shoemaker-Levy 9 during a close approach to Jupiter in 1992, after which the many resulting fragments collided spectacularly with the planet in July 1994.

Could we thus envisage a scenario in which loosely-bound Classical KBOs passing close to Neptune are broken up by tidal stresses and the fragments proceed to join the Excited TNO population? The answer must be no, because the resulting size distribution of fragments would not be poorer in small objects than the parent population, yet as noted above, the Excited population is much more strongly depleted at this end of the size range than the Classical population (see figure 3).

The only remaining possibility for replenishing the Jupiter-family comets would seem to be the breakup of relatively large Excited KBOs, say in the 10–100 km diameter range, as a result of encounters with Neptune. This could, in principle, generate thousands of smaller objects for every close encounter with Neptune, and thus conceivably produce an adequate supply of comet nuclei. However, it would also very likely replenish the small end of the Excited population itself, since more fragments are likely to join the Excited population than to move inwards in the solar system as Centaurs or comets. Once again, however, the extreme paucity of small Excited objects implies that this is not occurring on any significant scale; once again, it seems, this hypothesis does not solve the problem of supplying Jupiter-family comets for billions of years.

Hence, we may conclude, despite considerable uncertainties in the data, that the Jupiter family of comets cannot be sustained for billions of years by a Transneptunian population consistent with the best observationally-constrained estimates.

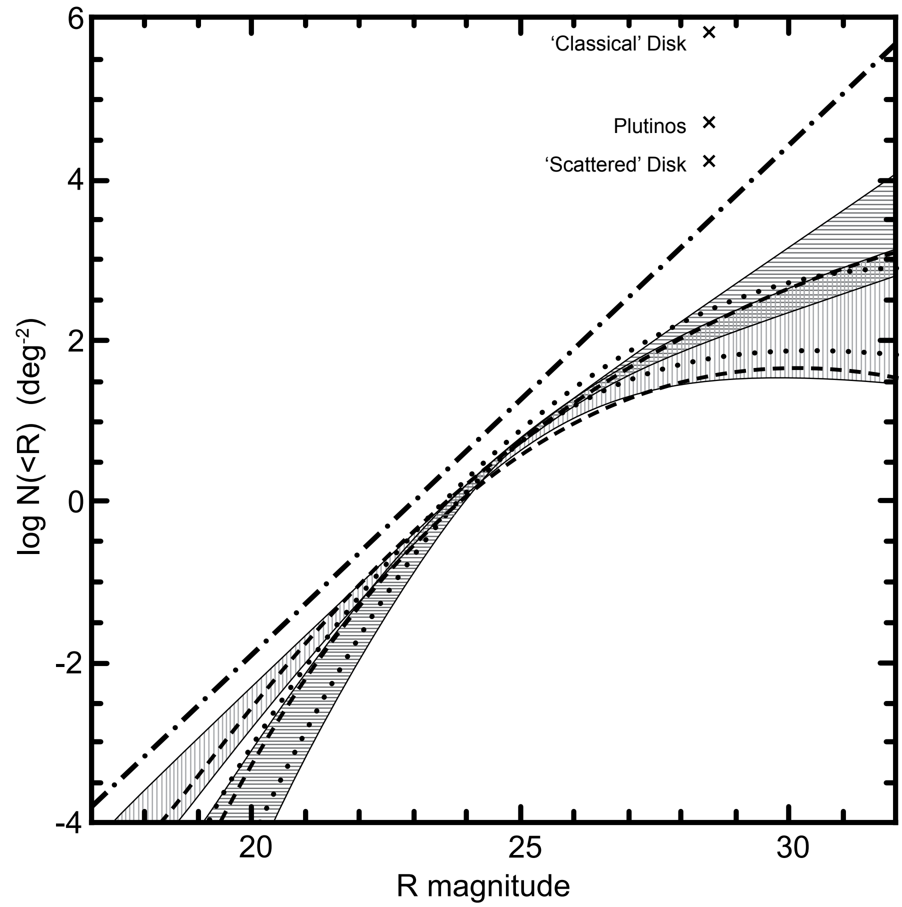

Figure 3. *The cumulative number of TNOs (N) per square degree of sky which are brighter than magnitude R. Different power-laws have been fitted to the data (hatched areas, dotted lines, dashed lines, see key) bounded by the 95% upper and lower confidence limits at each magnitude. The dot-dash line is a (now outdated) single power-law fit to the whole population. The X's in the upper right are based on models of the Kuiper Belt as a source of the Jupiter-family Comets; the assumed source population for each case is labelled. Note that the vertical scale is logarithmic and the smallest objects, which have the largest R magnitudes, correspond to the right-hand side of the diagram. (Based on fig. 8 in Bernstein* et al.*, ref. 16.)*

	Power-law fit		
	Single	Double	Rolling
Excited population		(vertical hatching)	-------------
Classical population		(horizontal hatching)	....
Total population	–·–·–·–·–·–·–		

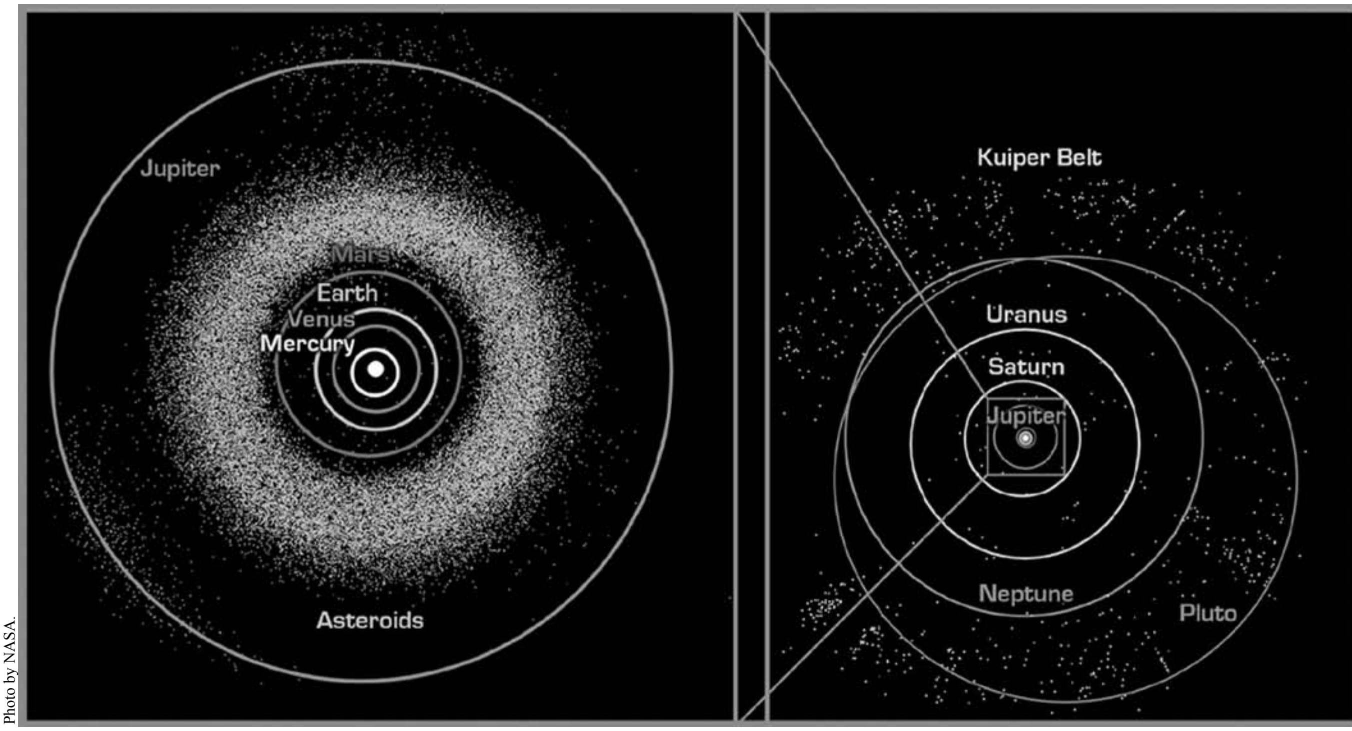

Photo by NASA.

Maps of the inner and outer solar system. Kuiper Belt objects are found dispersed around the orbit of Pluto.

Implications

The findings of Bernstein *et al.* do not shake their faith that the solar system is billions of years old. They provide several suggestions for bridging the huge gap between theory and observation, including: (i) the escape rate of comet precursors has been underestimated; (ii) important dynamical effects have been neglected, e.g. perturbations by Pluto or by undetected massive scatterers; (iii) large escaping KBOs may break up into fragments. It is not yet clear whether any of these can even begin to explain the discrepancy. A much simpler solution is that the solar system is not billions of years old, but has an age consistent with a biblical timescale of thousands of years. In a biblical framework it is not necessary to assume a cometary source reservoir which is stable over billions of years. It seems possible that there may have been a significant population of comet nuclei in the Transneptunian region, but that this was largely exhausted as they were perturbed and hurled into the inner solar system, producing major bombardments of the earth and other planets during Creation Week (or the Fall), and during the Genesis Flood, as suggested by Faulkner[32] and by Hartnett.[33] The perturbation mechanism is not discussed by these authors,[34] but Hartnett's use of 2 Peter 3:5–7 implies that God initiated the Flood bombardment. In this context it is interesting to note recent suggestions in the professional literature that the Late Heavy Bombardment of the inner solar system (beginning 3.85 billion years ago in the uniformitarian timescale) could have originated in the Kuiper Belt.[35]

The population of the Transneptunian region of the solar system is a hot research topic, and with improving search strategies and detection technologies, the coming decades can be expected to see the number of known objects rise well into the thousands, as well as significant changes in theoretical models. The most recent theoretical development is that of Levison and Morbidelli,[36] who have suggested that the present population was pushed outwards by interactions with Neptune, which itself was allegedly migrating outwards. Levison and Morbidelli make the usual unsubstantiated evolutionary assumptions, notably the outward migration of the outer planets through a thick disk of planetesimals over tens of millions of years.[37] Their model purports to explain why there is relatively little mass in the region, and why there appears to be an outer edge at about 50 AU: there never was much mass, and what there is hardly got beyond Neptune's 2:1 orbital resonance at 47.7 AU. However, the implied formation of the solar system from a truncated disk does not fit easily with observations of planetary systems apparently forming around other stars,[38] and the theory certainly does not explain the lack of a long-lived source for Jupiter-family comets.

Creationists should closely follow both observational and theoretical developments in this field to ensure that we are not caught out by repeating outdated arguments. Further investigation, possibly using computer simulations, may also be in order to clarify the role of collisions and of encounters with Neptune in producing orbital changes and fragmentation of KBOs, and perhaps to develop a model within a biblical framework for a catastrophic disruption of the Kuiper Belt resulting in a major bombardment of the inner solar system at the time of the Genesis Flood. However, for the present it is clear that the existence of Jupiter-family comets and the striking deficit of small TNOs together provide a strong argument in favour of a recently-created solar system.

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Bill Worraker has a B.Sc. (Hons) degree in Physics and a Ph.D. in Engineering Mathematics, both from the University of Bristol, U.K. He has experience of academic and industrial research into a wide range of fluid flow phenomena. Currently employed as a developer of industrial software, he has been an active amateur astronomer for over 20 years and has participated in collaborative professional-amateur observing projects on variable stars.