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The State of Knowledge Concerning the Kuiper Belt

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ABSTRACT

The arguments for and against the idea that most short-period comets originate in the Kuiper belt are discussed. Observational constraints on the distribution of mass in the Kuiper belt are reviewed as well as a model of the physical conditions that now exist. Finally, predictions from this model about the detectability of the Kuiper belt are compared to optical surveys.

INTRODUCTION

There has been a lot of interest recently in the idea the most of the short-period comets (SPC, $P \lesssim 200 years$) originate in disk of material that lies just beyond the orbit of Neptune. The idea was first put forward by Fernández (1980), but the current interest was prompted by a paper by Duncan, Quinn, & Tremaine (1988). This disk of material has come to be known as the Kuiper belt. A significant amount of research, both observational and theoretical, has been done since the publication of Duncan, Quinn, & Tremaine. Thus, it was decided to have a special session on the Kuiper belt at this meeting. I was asked to present a review talk on this topic. This paper summarizes that presentation.

For the purpose of this paper, I divide SPC into two groups. Halley-family comets (HFC) are those comets with periods between 20 and 200 years, Jupiter-family comets (JFC) are those objects with periods less than 20 years. These classifications are not arbitrary because these two groups appear to have very different dynamics. JFC are always found in low inclination prograde orbits. The mean inclination of JFC is 10°. The distribution of HFC is somewhat more isotropic, having a mean inclination of 41°. Several Halley-family comets are on retrograde orbits, including Halley itself. Recall that the long-period comets are isotropic. Any theory that attempts to explain short-period comets must explain the observed inclination distribution.

It was usually believed that SPC originated in the Oort cloud and evolved into SPC through gravitational interactions with the planets (Newton 1893, see also Everhart 1972). In recent years several lines of argument have been put forward that put doubt on this idea, see Levison (1992) for a complete review. In my opinion, the strongest of these is that it is not possible to reproduce the inclination distribution of JFC from the spherical distribution of long-period comets. Since space in this paper is somewhat limited, I only discuss this point. I also only consider the two most recent papers on this subject; Quinn, Tremaine, & Duncan (1991), hereafter QTD, and Stagg & Bailey (1989), hereafter SB.

These two papers use very different methods to integrate the orbits of a large number of test particles. These particles are initially on Neptune-crossing orbits and they are followed until they become 'visible' comets ($q < 1.5AU$ for QTD and $q < 2.5AU$ for SB). This is a very difficult problem because the evolution time scale is very long. Both sets of authors needed to adopt some simplifications in order to perform the integrations. SB treated the problem as a stochastic process, giving the particles energy kicks in a well defined, but random fashion. The inclination of the particles is assumed to be constant and the change in perihelion distance is calculated from the Tisserand parameter. QTD directly integrate the orbits of the particles, but in order to decrease the time scales they increased the mass of the planets by a factor of 10. In my opinion, neither of these methods are very satisfactory and both will produce inaccurate results. However, I think that QTD's method is more physical and hence more likely to produce the more accurate orbit integrations. Another problem with both papers is that orbits are only followed until they become visible comets. Neither set of authors allow one type of short-period comet to evolve into another. Lingren (1991) has shown that the orbits of visible comets can significantly change over a comet's lifetime. Indeed, a comet can become visible, evolve to large perihelion distances, can become visible again, and so on over its lifetime. Therefore, it is not strictly appropriate to compare the orbital element distribution of SPC derived by SB and QDT to the observed distribution.

The results of the two papers agree on several important points. They both conclude that HFC are most likely captured long-period comets. They both agree that in order to *dynamically* produce a very flat distribution of comets, the comets must have started in a very flat distribution. Note that SB assumes that the inclination of a comet remains constant. Thus, the inclination distribution of JFC cannot be reproduced from captured long-period comets unless some non-dynamical effects are included. For example, SB suggests that it may take longer for high inclination comets to become captured. These older comets may be fainter and thus less likely to be discovered. The flat distribution of JFC may be a selection effect. QDT attempt to model this and find that this selection effect is not strong enough to explain the observations.

The papers disagree as to whether the Kuiper belt can be the source of the JFC. SB finds that only about a third of the objects that start on low inclination, prograde, Neptune-crossing orbits become Jupiter-family comets. The rest become Halley-family comets. Thus they argue that it is not possible to reproduce the flat distribution of JFC and the more isotropic distribution of the HFC from the Kuiper belt. Indeed, they cannot explain the JFC with strictly dynamical effects, and as stated above they suggest a few non-dynamical processes that may produce them. Contrary to this, QTD find that all objects that start on low inclination, prograde, Neptune-crossing orbits become Jupiter-family comets, and thus, the Kuiper belt can be the source for the JFC. I think that it is clear from my previous comments that both these papers have some problems. To resolve this dispute, better calculations must be performed. This may be possible within the next few years as computers become faster and numerical methods become more powerful. As I stated above, I believe that the approximations made by QTD are more accurate than those used by SB.

It is now possible to construct a 'complete theory' of the origin of Jupiter-family comets. As Kuiper (1951) pointed out, it seems likely that the disk of planetesimals that formed the planets would not have abruptly ended at the orbit of Neptune, but would have extended far outside the planetary region. The composition of the objects that formed in this region is most likely similar to the satellites of Neptune and Uranus and thus presumably resembles present day comets.

Torbett (1989) and Torbett & Smoluchowski (1990) have shown that all particles with initial values of perihelion distance less than $\sim 45AU$ and eccentricity greater than ~ 0.01 are chaotic on timescales of 10 million years and therefore can in principle leave the Kuiper belt. However, they could not predict the time scale on which objects leave this region. In two previous papers (Levison 1991a and Levison 1991b, hereafter L1 and L2 respectively) I have shown that the timescale for objects leaving the Kuiper belt is on the order of the age of the solar system. I predict that approximately 50% of the objects the formed in the Kuiper belt are still there and yet they are leaving in large enough numbers to explain the Jupiter-family comets. However, I must point out that there are some possible problems with the technique that I employ in these papers, which essentially treats the long-term behavior of objects as a diffusion problem in orbital element space. The diffusion coefficients are calculated from relatively short direct orbit integrations. It is possible that the diffusion coefficients I calculate are too large if very long-period oscillations exist because they will be included in the drift rates. See L1 for a complete discussion of the draw backs of this technique. Finally, QTD have shown that these objects evolve into a population with orbital parameters consistent with those of Jupiter-family comets.

PHYSICAL CHARACTERISTICS OF THE KUIPER BELT

I now address our limited understanding of the physical characteristics that currently exists in the Kuiper belt. Unfortunately, very few observational constraints can be applied to the Kuiper belt. I start by discussing the size distribution of comets.

Shoemaker & Wolfe (1982) show that the number of comets with radii between a and $a + da$, $n(a)da$, follows a power law, a^{-3}. They derive this number from studying the magnitude distribution of comets as well as the distribution of crater sizes on Ganymede. Unfortunately, their work does not extend to very big comets. The large objects are interesting because they present our only opportunity to observationally detect objects in the Kuiper belt. If all comets were less than or approximately the same size as Halley, it would be impossible to detect them outside the orbit of Neptune with current technology.

There are two arguments that suggest that very large objects may reside in the Kuiper belt. Chiron, which is a roughly $100km$ sized object, is on a Saturn-crossing orbit that is unstable on a timescale of 10^5 – 10^6 years (Oikawa & Everhart 1979). It has recently been discovered to exhibit cometary behavior (Luu & Jewett 1990) such as the formation of a resolved coma (Meech & Belton 1990). Because of the short lifetime of its current orbit, it seems likely that Chiron originated farther out in the solar system and that it is representative of a much larger population of similar objects which currently reside in the Kuiper belt.

Somewhat more speculatively, Stern (1991) argues that there may be a few Pluto sized objects in the Kuiper belt. His argument is based on the fact that the three 'pluto-like' objects in the solar system; Pluto, Charon, and Triton; are found on very rare but long-lived orbits. The most reasonable way to explain how these orbits got populated is to envision a large number of pluto-like objects in the outer solar system at early epochs. The number of such objects was large enough so that we expect that a few rare long-lived orbits will be populated. The objects not on long-lived orbits have since been removed from the solar system. A few of these objects may still be in the Kuiper belt.

Thus, it seems reasonable to speculate that there are objects as large as Chiron, and perhaps as large as Pluto, in the Kuiper belt. But it is clearly not appropriate to assume that Shoemaker & Wolfe's power law extends to large objects. Following Levison & Duncan (1990), let the number of comets, n, with radii between a and $a + da$, be

$$n(a) \propto \begin{cases} 0 & \text{if } a < a_{cut} \\ a^{-(b_1+1)} & \text{if } a_{cut} \leq a < a_0 \\ a^{-(b_2+1)} & \text{if } a \geq a_0 \end{cases}, \tag{1}$$

where a_0 is the radius where the power law breaks and a_{cut} is the smallest object that can become a visible short period comet. The parameters b_1 and b_2 are constants. This follows Tremaine (1990) except that he sets $a_{cut} = 0$. He argues that $3 \leq b_2 \leq 7$ and sets $a_0 = 10km$. As stated above, Shoemaker & Wolfe (1982) show that $b_1 = 2$. Levison & Duncan use $a_{cut} = 0.75km$.

It is possible to calculate the total mass of the Kuiper belt using the available numerical models. The rate at which Jupiter-family comets are being produced, R_{JFC}, is simply

$$R_{JFC} = N_{KB}\ r_{Nx}\ f_{JFC}, \tag{2}$$

where N_{KB} is the current number of comets in the Kuiper belt, r_{Nx} is the fraction of particles that leave the Kuiper belt per year, and f_{JFC} is the fraction of particles the become Jupiter-family comets once they leave the Kuiper belt. Fernández (1985) assigned a value of $10^{-2}yr^{-1}$ to R_{JFC}. However, this value is very uncertain because of the uncertainty in the mean lifetime of Jupiter-family comets. The true value of R_{JFC} may differ from Fernández by as much as a factor of 10. From their numerical integrations DQT found that $f_{JFC} = 0.17$. In L2 I found that $r_{Nx} = 4 \times 10^{-11}yr^{-1}$. Using these values, there are approximately 1.5×10^9 comets in the Kuiper belt. Weissman (1990) states that the mean mass of a comet is $6.4 \times 10^{-12} M_\oplus$. Thus the total mass in the Kuiper belt is $0.01 M_\oplus$. This is quite small and it would not be possible to detect the gravitational effects of this amount of mass on other objects in the solar system (Tremaine 1990 and Hogg, Quinlan, & Tremaine 1991). Recall that these numbers may vary by as much as a factor of 10 because of the uncertainty in R_{JFC}.

I presented a model for the current density distribution in the Kuiper belt in L2. This model predicts that the density of objects is quite small at $45AU$. The density quickly increases with distance from the sun until it peaks at about $70AU$. Unfortunately, this result implies that the Kuiper belt will be much harder to observationally detect than previously thought, because, most observers have assumed that most of the mass in the Kuiper belt is at about 45 or $50AU$.

DETECTABILITY OF THE KUIPER BELT

There have been several optical surveys to search for slow moving objects in the outer regions of the solar system. Typically, the searches cover a particular area of the sky down to some limiting magnitude. No objects beyond Neptune were found. From this it is possible to calculate a upper limit for the number of objects per square degree brighter than the limiting magnitude of the survey, Σ_{obs}. The limit of each survey is plotted in Figure 1 as a function of limiting magnitude. The symbol marked with a 'T' refers to a survey by Tombaugh (1961) that covered $1530(deg)^2$ to a limiting magnitude of 17.5 in V. Luu & Jewett (1988) performed a survey that covered $200(deg)^2$ to a limiting magnitude of 20 in V using a Schmidt telescope, labeled LJ(S). They also searched an area of $0.34(deg)^2$ using a CCD system. They state that this survey reached a limiting magnitude of 24 in R, or approximately 24.5 in V, labeled LJ(C). The symbol labeled 'K' refers to Kowal (1989) which covered $6400(deg)^2$ to a limiting magnitude of approximately V = 20. The symbol labeled 'LD' refers to Levison & Duncan (1990) which covered $4.9(deg)^2$ to a limiting magnitude of approximately V = 23.5. Notice that all of the surveys outlined here would be unable to detect Chiron at distances from the Sun greater than $55AU$.

From the model presented in the last section, would we have expected to find objects with these surveys? In L2, I projected the model into the sky and calculated Σ as a function of magnitude. I assumed that the albedo of the objects is 0.1 and that all the objects lie within 10° of the ecliptic. This value is plotted in Figure 1 as a function of magnitude for 3 values of b_2. Note that none of the searches are near my predictions and, therefore, it is not surprising the no objects were found. If my predictions are correct then future searches need to either survey about an order of magnitude more area of the sky or go approximately 2 magnitudes fainter!

CONCLUDING REMARKS

The only possible *dynamical* explanation for the inclination distribution of Jupiter-family comets is that they originate in a disk of material that lies just beyond the orbit of Neptune. However, there is some disagreement at to whether this model indeed works. More accurate numerical models must be constructed. I tend, however, to trust the results of Quinn, Tremaine, & Duncan (1991) who claim that the model does indeed work.

If the numerical models are accurate, then it is possible to put constraints on the current physical conditions of the Kuiper belt. The combination of the results from QDT and L2 predicts that there are approximately 10^9 comets in the Kuiper belt with a total mass of approximately $0.01 M_{\oplus}$. Most of this mass will be beyond $60 AU$ from the Sun. Again, this makes it very difficult to detect. The only optical search that I believe can succeed is one that goes very faint and covers a large area of the sky (tens of square degrees).

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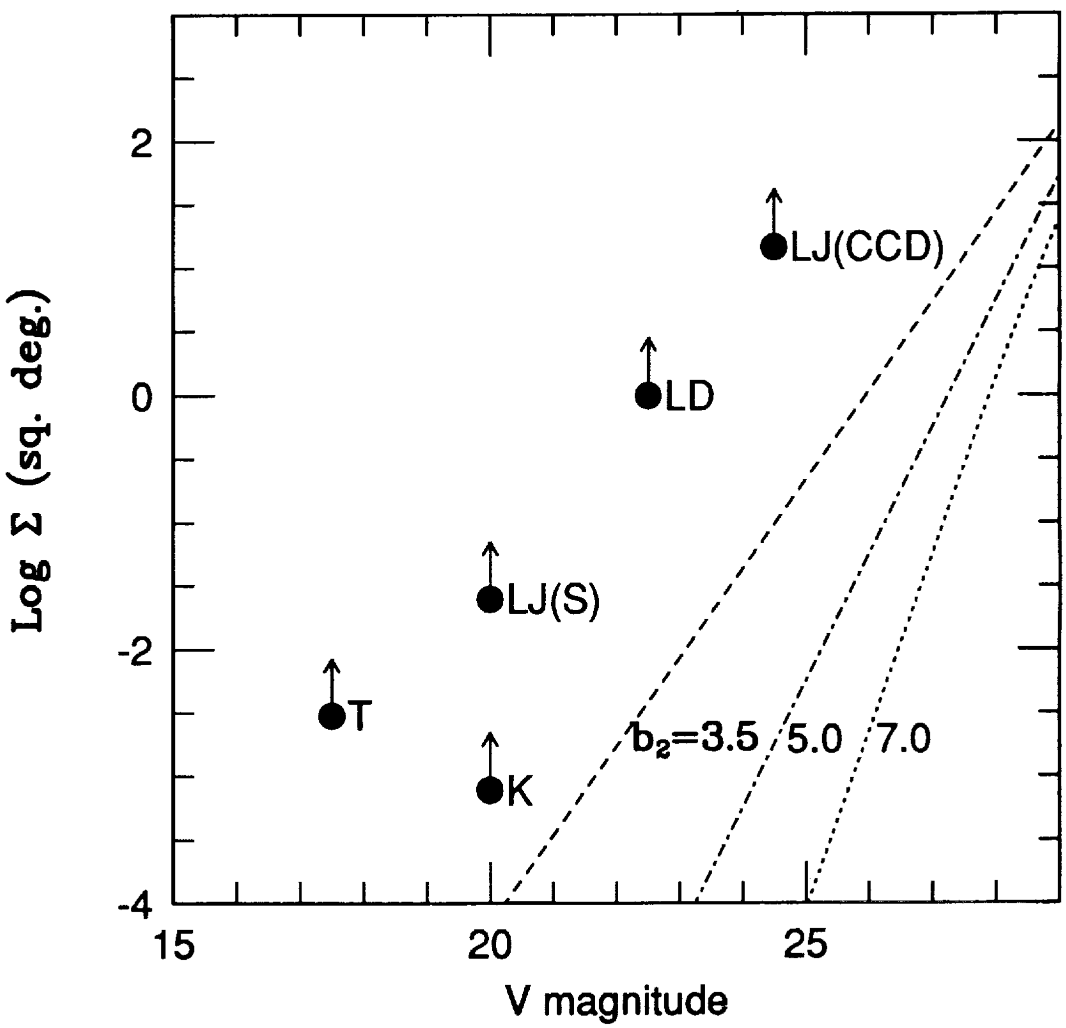

FIGURE 1 — **The number of observable Kuiper belt objects per square degree, Σ, as a function of a** survey's limiting magnitude in V. The curves represent our model with different values of b_2. The marked symbols refer to lower limits of real surveys: $T \rightarrow$ Tombaugh (1961), $K \rightarrow$ Kowal (1989), $LJ \rightarrow$ Luu & Jewitt (1988), $LD \rightarrow$ Levison & Duncan (1990). Luu & Jewitt performed two searches. The results of their search with a Schmidt telescope is marked with a (S), and the results of their CCD search is marked with a (CCD). See Levison & Duncan for complete discussion.