Completing the Inventory of the Solar System
ASP Conference Series, Vol. 107, 1996
T. W. Rettig and J. M. Hahn, eds.

Comet Taxonomy

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Abstract. The current comet classification scheme is reevaluated in terms of the most recent models of the origin and dynamical evolution of comets and is found to be wanting. After a review of the current theories of the origin of comets and of the results of recent numerical simulations, a new taxonomy is developed. The main division between comets is defined by the Tisserand parameter, T, which is a measure of the influence of Jupiter on the dynamics of the comets. Comets with $T < 2$ are called 'nearly-isotropic' comets because they have a fairly uniform inclination distribution. Comets with $T > 2$ are designated as 'ecliptic' comets because of their very flat inclination distribution. Long-term dynamical integrations by Levison & Duncan (1994) have shown that over 90% of comets with periods currently less than 200 years remain in one of these two classes throughout their dynamical lifetimes. These new classes are thus dynamically significant and probably reflect the origin of the comets they contain. These classes are further subdivided as described below. In addition, this new scheme is compared to an exciting new classification scheme based on the chemical abundances of comets.

1. Introduction

The usual first step in the study of any new type of object or phenomenon is to develop a classification scheme or taxonomy. This practice is particularly widespread in astronomy, where it has been applied to everything from solar system dust particles to clusters of galaxies. The main purpose of these classification schemes is to allow us to organize our thoughts. In particular, they allow us to put the objects of study into a structure in which we can look for correlations between various physical parameters and begin to develop evolutionary models. In this way, classification schemes have played, and continue to play, [1] a crucial role in advancing our understanding of the universe.

There are times in the history of any field of study when we have learned enough to reevaluate our classification schemes. These times occur when new

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[1] We must be careful not to confuse these schemes with reality. In many cases, we are forcing a classification scheme on a continuum of objects. Then we argue over where to draw the boundaries. The fact that we astronomers find cubbyholing objects convenient does not imply that the universe will necessarily cooperate.

ideas about the origin and evolution of the objects of interest have been developed and have become accepted by the majority of the scientific community. The new classification schemes should reflect these new ideas. This does not mean these new ideas must be undisputed. On the contrary, one reason for developing a new scheme is to provide a framework for the evaluation of these new ideas.

Perhaps we, as a community, have reached such a time in the history of the study of comets. This is particularly true with regard to their origin and their dynamical evolution. Recently, technical advances in our ability to perform long-term numerical orbital integrations of solar system objects have allowed us to make tremendous progress in understanding the early dynamical evolution of comets. In the past few years, the capacity of the astronomical community to perform these integrations has increased by several orders of magnitude. This really incredible increase is due to a combination of the availability of fast, low-cost computer workstations and the development of sophisticated but highly efficient computer algorithms. These tools have allowed us to directly follow the dynamical behavior of comets in the solar system throughout entire evolutionary phases. These integrations have aided in the development of a fairly complete model of the origin and dynamical evolution of comets. This new model is employed below to develop a new cometary classification scheme.

This article is organized as follows: Section 2 discusses the 'currently accepted' comets classification scheme. Section 3 presents models for the formation of the cometary reservoirs. Section 4 discusses some of the lessons learned from recent long-term dynamical integrations of short-period comets, and Section 5 presents a proposed new classification scheme. Comet classification schemes have traditionally been based on orbits. This trend is continued in most of this paper. However, Section 6 discusses some chemical abundance considerations.

2. Current Cometary Classification Scheme

Astronomers have been classifying the orbits of comets for centuries. A complete history of this topic is beyond the scope of this paper. Instead, this section discusses the currently accepted cometary classification scheme. This scheme is illustrated in Figure 1, which shows the comet family tree.

First and foremost, comets have been historically divided into two classes: long-period comets (with periods greater than 200 years) and short-period comets (with $P < 200$ years). This division was developed to help observers determine whether a newly discovered comet had been seen before. Since orbit determinations have been reliable for only about 200 years, it may be possible to link any comet with a period less than this length of time with previous apparitions. Conversely, it is very unlikely to be possible to do so for a comet with a period greater than 200 years, because even if it had been seen before, its orbit determination would not have been accurate enough to prove the linkage. Thus this division, the most fundamental one in our family tree, has no physical justification and is now of historical interest only. As a result, it should be removed from any revamped scheme.

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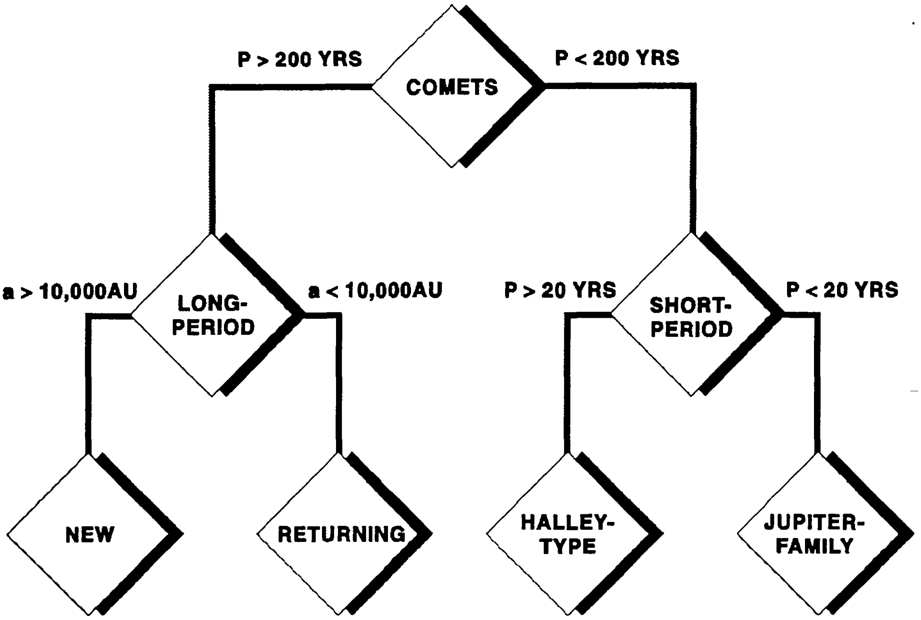

Figure 1. The currently accepted family tree for comets.

2.1. Long-Period Comets

Long-period comets have been divided into two groups: dynamically 'new' comets and 'returning' comets. This division is one that has its roots in the dynamics of these objects and is based on the distribution of their semi-major axes, a. Figure 2 shows a histogram of $1/a$, which is proportional to orbital binding energy. [2] The most striking feature of this plot is the peak at about $a \sim 20,000$ AU. This feature led Oort (1950) to conclude that the solar system is surrounded by a spherically symmetric cloud of comets, which we now call the Oort cloud. [3]

The peak in the $1/a$ distribution of long-period comets is fairly narrow. And yet the typical kick that a comet receives when it passes through the planetary system is approximately $\pm 0.0005\,\mathrm{AU}^{-1}$ (Oort 1950, cf. Figure 2). Thus it is unlikely that a comet that is in the peak when it first passes through the solar system will be in the peak during successive passes. It is concluded from this argument (Oort & Schmit 1951) that comets in the peak ($a \gtrsim 10,000\,\mathrm{AU}$) are dynamically 'new' in the sense that this is the first time that they have passed through the planetary system.

Comets not in the peak are most likely objects that have been through the planetary system before. Comets with $a \ll 20,000\mathrm{AU}$ that are penetrating the planetary system are ejected from the solar system on a timescale that is much less than that for their replenishment from the Oort cloud (Weissman 1979; Hills 1981; Heisler & Tremaine 1986; Duncan, Quinn, & Tremaine 1987). There-

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[2] Recall that $1/a < 0$ implies that the comet is unbound.

[3] It is interesting to note that there were only 19 comets in the Oort's original histogram.

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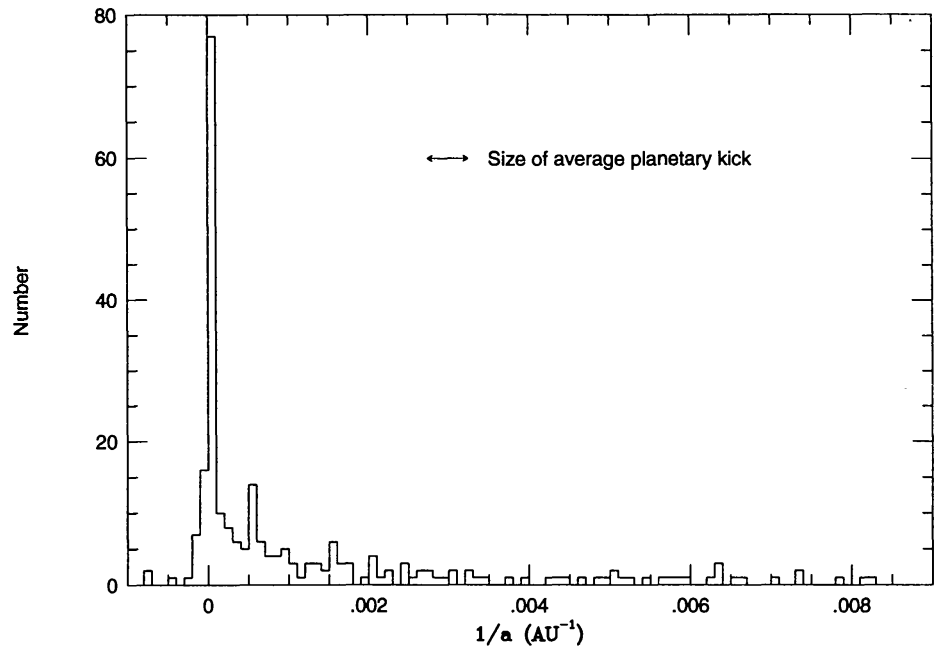

Figure 2. The distribution of inverse semi-major axis a for the long-period comets in Marsden's (1992) catalog.

fore, we should not expect to see any dynamically new comets with semi-major axes smaller than this value. We can conclude that any long-period comet not in the peak is a comet that was initially in it but has evolved to smaller a during previous passes through the planetary system. These comets are called 'returning' comets. The boundary between new and returning comets has in the past been placed between 5000 AU and 20,000 AU. Here, a dividing line of 10,000 AU is adopted.

2.2. Short-Period Comets

Short-period comets have also been typically divided into two groups. The main motivation for this division can be seen in Figure 3, which plots the inclination of short-period comets as a function of their semi-major axis. First notice that there is a strong concentration of objects with semi-major axes between 3 and 4 AU. These objects tend to have aphelion close to the orbit of Jupiter and tend to have small encounter velocities with it. Thus they are dynamically dominated by that planet and have come to be known as 'Jupiter-family' comets.

The observed Jupiter-family has a very flat inclination distribution; its mean inclination is 10°. All Jupiter-family comets are on prograde (direct) orbits. This is to be compared to those comets that are not members of the Jupiter-family, which have a mean inclination of 41° and several of which are on retrograde orbits. These comets are known as Halley-type comets. [4]

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[4] In previous papers I and others have called this classification Halley-family comets. However, Hans Rickman has pointed out that the word 'family' has a special meaning in that the object

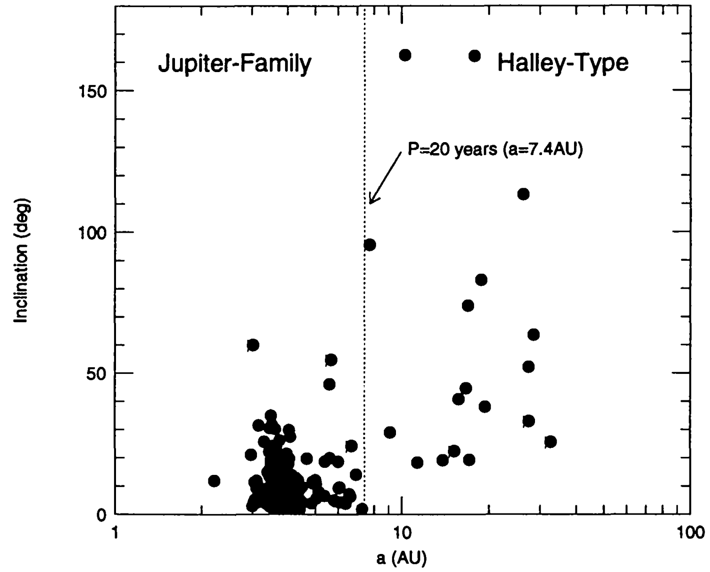

Figure 3. The inclination distribution of short-period comets as a function of semi-major axis a. The vertical dotted line shows the traditional division between Jupiter-family and Halley-type comets at $P = 20$ years.

The boundary line between the Jupiter-family and the Halley-type comets has traditionally been drawn in terms of orbital period, usually 15 or 20 years, or aphelion distance (usually 10 AU). The most commonly quoted value is $P = 20$ years. This boundary is marked as a vertical dotted line in Figure 3. The apparent discontinuous jump in the inclination distribution of short-period comets near this point is an indication that the Jupiter-family and Halley-type comets are dynamically distinct groups, and may have different origins (see Section 3 for more details).

It should be noted that Carusi et al. (1987a) suggested defining the boundary between Jupiter-family and Halley-type comets along a line of constant Tisserand parameter, $T = 2$. The Tisserand parameter is usually defined as

$$T = a_J/a + 2\sqrt{(1-e^2)a/a_J}\ \cos(i), \tag{1}$$

where a_J is Jupiter's semi-major axis. It is an approximation to the Jacobi constant, which is an integral of the motion in the circular restricted three-body problem. It is also a measure of the relative velocity between a comet and Jupiter during close encounters, $v_{rel} \propto \sqrt{3-T}$. Objects with $T > 3$ cannot cross Jupiter's orbit in the circular restricted case, being confined to orbits either totally interior or totally exterior to Jupiter. A possible argument against using T as a discriminator between the Jupiter-family and Halley-type comets is that

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for which the class was named is the planet that dynamically dominates the comets in it. For example, Jupiter-family comets are dynamically dominated by Jupiter. The comets in this class have no such connection and thus this class should be called Halley-type.

by accepting this definition we build our preconceived biases about the long-term behavior of short-period comets (that T is approximately constant) into our definitions. As we will see in Section 4, this fear is unfounded.

3. Comet Reservoirs

One of the principal motivations for reexamining our current classification scheme is the progress that has been made in understanding where the current crop of visible comets has come from. The median dynamical lifetime of long-period and short-period comets is 6×10^5 years (Weissman 1979) and 5×10^5 years (Levison & Duncan 1994), respectively. Therefore, the objects that we see today must have been stored in one or more cometary reservoirs outside the planetary region for billions of years before being injected into the inner solar system where they can be observed.

3.1. The Oort Cloud

As described above, long-period comets originate in the Oort cloud, which is a nearly spherical distribution (at least in the outer regions) of comets, centered on the Sun. The position of its inner edge is very uncertain. The position of its outer edge is defined by the solar system's tidal truncation radius at about $1 - 2 \times 10^5$ AU from the Sun (Smoluchowski & Torbett 1984).

The orbits of comets stored in the Oort cloud evolve due to the gravitational effects of the galactic disk (Heisler & Tremaine 1986, Bailey 1986), passing stars (Oort 1950, Hills 1981), and passing giant molecular clouds (Biermann & Lüst 1978, Weissman 1990). Since these perturbations to first order act as a torque, the semi-major axis of a comet remains fixed while its perihelion distance undergoes a random-walk. Occasionally, a comet will evolve so that its perihelion distance falls to within a few AU of the Sun, thus becoming a visible long-period comet. As discussed above, Hills (1981) pointed out that we should see only objects with $a \sim 2 \times 10^4$ AU, although the Oort cloud itself probably extends much closer to the Sun.

The objects that we see as long-period comets have been stored at great distances from the Sun for nearly the age of the solar system. However, it is most likely that they were formed in the outer regions of the solar system (Kuiper 1951), primarily near Uranus and Neptune (Safronov 1972). That is, the comets now in the Oort cloud are thought to have formed in nearly circular orbits in the Uranus-Neptune region of the solar system and to be the remnants of planetary formation. Their semi-major axes evolved in a random walk because of repeated gravitational scattering by Uranus and Neptune. (Jupiter and Saturn are so massive that they tended to eject objects from the Solar system, cf. Tremaine 1993.) When the semi-major axes of these bodies reached about 10^4 AU, galactic perturbations lifted their perihelia out of the planetary system where they were stored for billions of years. Although other theories for the origin of the Oort cloud have been proposed (a complete discussion is beyond the scope of the paper, see Fernández 1985 or Weissman 1985 for a review), this theory has become the dominant one.

Perhaps the most complete numerical simulation of the formation of the Oort cloud was one performed by Duncan, Quinn, & Tremaine (1987). In this

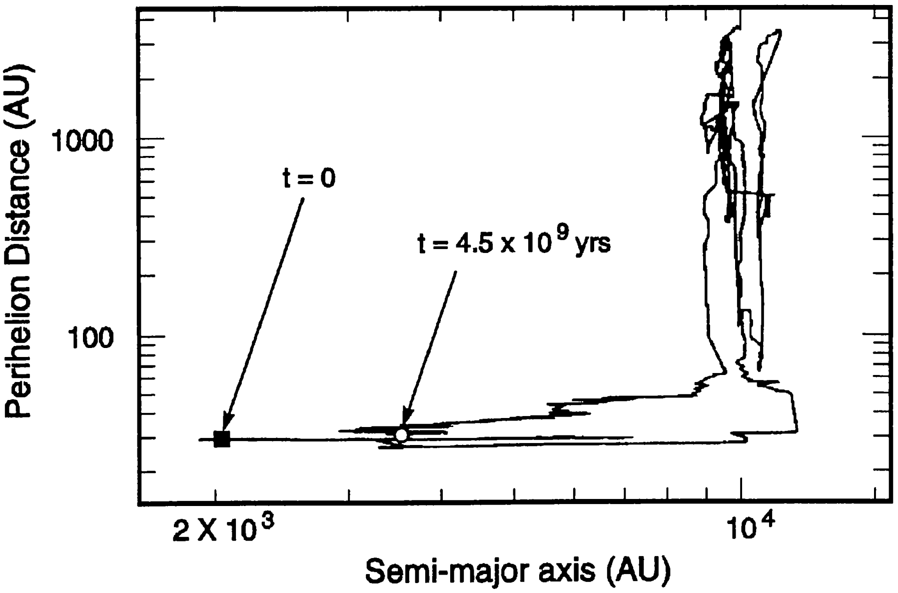

Figure 4. The evolution in semi-major axis and perihelion distance for a typical comet in the calculation by Duncan, Quinn, & Tremaine (1987).

work, they followed the orbital evolution of a large number of comets, initially on low inclination orbits with $a = 100\,\mathrm{AU}$, under the gravitational influence of the giant planets, stellar encounters, and galactic tides. Figure 4 shows the behavior of a typical comet in their calculations. Early in the simulation, when the comet penetrates the planetary system but its semi-major axis is too small for galactic perturbations to be important, there is a random walk in a at a constant perihelion distance, q (see also Yabushita 1980). When a grows to approximately 10^4 AU, the galaxy becomes important and the perihelion distance gets lifted beyond the planetary system. The comet can be stored in this state for very long periods of time. Duncan et al. found that a structure similar to the Oort cloud is formed (see their Figure 4). Their Oort cloud is spherically symmetric for $a \gtrsim 5000\,\mathrm{AU}$ and has a density profile that is approximately proportional to $r^{-3.5}$ between 3000 and 50,000 AU. In addition, they demonstrated that individual comets can drift back into the planetary region after being stored in the Oort cloud for very long periods of time becoming long-period comets. The comet in Figure 4 begins to show this behavior.

3.2. The Kuiper Belt

In recent years our ideas concerning the origin of the short-period comets has changed drastically. The traditional explanation for their origin is that they are Oort cloud comets which have been captured into short-period orbits as a result of gravitational interactions with the planets (Newton 1893; see also Everhart 1972). The primary alternative is that they originate in a disk of material lying just beyond the orbit of Neptune. This idea was reintroduced by Fernández (1980), after the original suggestion of a trans-Neptunian planetesimal disk by Edgeworth (1949), and again by Kuiper (1951).

The Kuiper Belt origin began to gain widespread acceptance with the publication of Duncan, Quinn, and Tremaine (1988). The authors of this paper were the first to directly integrate the orbits of objects from beyond the planetary region until they were either ejected from the solar system or became visible. They studied objects that originated in both the Kuiper Belt and the Oort cloud and concluded that the Oort cloud could not be the source of most short-period comets. In a later study, Quinn, Tremaine, & Duncan (1990) argued on the basis of improved calculations that: *i*) it is not possible to dynamically reproduce the apparent inclination distribution of the Jupiter family from the spherical distribution of Oort cloud comets, but that *ii*) objects leaving the Kuiper Belt do reproduce the observed orbital element distribution of the Jupiter-family. They concluded that most of the Jupiter-family comets originated in the Kuiper Belt while most of the Halley-type originated in the Oort cloud. Unfortunately, owing to the limitations of the computing power available at that time, the authors were forced to adopt several assumptions that have been questioned by other workers (e.g., Stagg & Bailey 1989; Rickman 1990; Bailey 1992).

Since the publication of Duncan, Quinn, and Tremaine (1988), work on both the observational and theoretical fronts has bolstered support for the Kuiper Belt origin. Observational evidence for the existence of the Kuiper Belt has been furnished by the discovery of 32 Chiron-sized objects from the ground and the detection of $\sim$ 40 comet-sized objects using HST (Cochran et al. 1995) in this region (see Weissman & Levison 1996 for a review). About 20 of the Chiron-sized objects now have their orbital elements determined well enough to show that they are members of the proposed comet belt.

In addition, very long-term numerical simulations have been performed of test particles in the Kuiper Belt. These studies followed objects in nearly circular orbits in the Kuiper Belt until they become visible short-period comets. In this way, it has been possible to construct a fairly complete theory of the formation of Jupiter-family comets.

The theory states that Jupiter-family comets are planetesimals that formed in nearly circular orbits outside the orbit of Neptune. Numerical integrations have shown that orbits with perihelia within 45 AU of the Sun are chaotic (Torbett 1989; Torbett & Smoluchowski 1990) and thus may be unstable. Objects initially in nearly circular chaotic orbits in the Kuiper Belt can remain relatively stable for long periods of time and then become grossly unstable and become Neptune-crossers (Levison & Duncan 1993; Holman & Wisdom 1993). Thus they leave the Kuiper Belt.

The most complete study of orbits in the Kuiper Belt has been undertaken by Duncan, Levison, & Budd (1995), who followed the orbits of a thousand particles in the Kuiper Belt for the age of the solar system. The results of this integration are shown in Figure 2 of Alan Stern's Kuiper Belt review article in this volume. This figure shows the length of time it takes for a particle to become a Neptune-crosser as a function of its initial orbital elements. As can be seen from the figure, the Kuiper Belt has a complex structure. One of the most important results from this calculation is that there are regions in the Kuiper Belt where objects are stable for several billion years, after which they go unstable and become Neptune-crossers. This result implies that there are objects leaving the Kuiper Belt today and thus the Kuiper Belt can be the source of

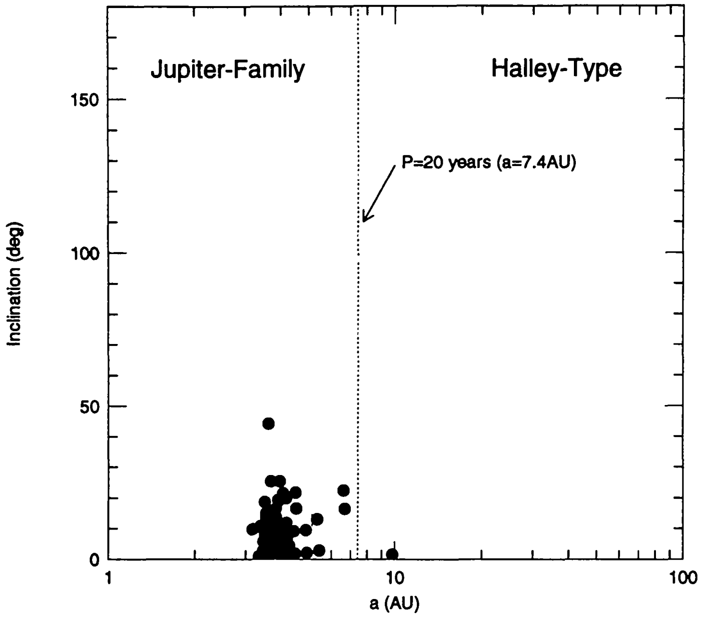

Figure 5. The inclination distribution of hypothetical short-period comets that originated in the Kuiper Belt as a function of their semi-major axis a. The vertical dotted lines shows the division between Jupiter-family and Halley-type comets at $P = 20$ years.

Jupiter-family comets. It is interesting to note that the currently active region of the Kuiper Belt is quite large, ranging from $a \approx 36\,\mathrm{AU}$ to $a \approx 43\,\mathrm{AU}$ if the eccentricity of Kuiper Belt objects is $\lesssim 0.05$ and even larger if the eccentricity is higher. In addition, the objects 1993FW (which is marked in the figure) is in a currently active region, thus showing that the active regions of the Kuiper Belt are currently populated.

Martin Duncan and I are working on a project where we follow the orbits of objects that left the Kuiper Belt in the last billion years until they become visible (defined as $q < 2.5\,\mathrm{AU}$) short-period comets. This work is far from complete and our statistics are as yet not very good. However, we have found that approximately a third of the objects that leave the Kuiper Belt become visible short-period comets. [5] The semi-major axis – inclination distribution for these hypothetical comets is shown in Figure 5. A comparison with Figure 3 shows that objects from the Kuiper Belt do indeed evolve into visible comets that have orbital elements almost identical to Jupiter-family comets. [6] However, the Kuiper Belt does not appear to produce any (or at least many) Halley-type comets.

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[5] This is significantly larger than the fraction (17%) reported by Duncan, Quinn, & Tremaine (1988). Most likely this difference is due to the fact that they had to make several assumptions in order to perform their calculations, including increasing the mass of the planets by at least a factor of 10 and placing the planets on fixed orbits. We, on the other hand, performed a full N-body calculation with no such assumptions.

[6] In agreement with the results of Quinn, Tremaine, & Duncan (1990).

In sum, the recent work outlined above has shown that: *i*) There are regions of the Kuiper Belt that are currently active. This is, objects in these regions can be stable for the age of the solar system, after which they go unstable and become Neptune-crossers. *ii*) 1993 FW is in one such region, showing that these regions are currently populated. *iii*) A significant fraction of these objects will become Jupiter-family comets once they leave the Kuiper Belt. Thus, there are solid theoretical and observational reasons to conclude that the Kuiper Belt is the source for most of the Jupiter-family comets.

4. Lessons of Long-Term Orbital Integrations

Another reason for reevaluating our current cometary classification scheme is that we now have very long-term numerical integration of the orbits of the short-period comets (Levison & Duncan 1994). This integration allows us to statistically study the long-term behavior of comets. With particular relevance to the question of cometary taxonomy is the fact that this integration teaches us whether objects can move between our classes, which in turn is very important in determining the validity of any classification scheme.

In Levison & Duncan (1994), Martin Duncan and I integrated the orbits of the known short-period comets under the influence of the Sun and all the planets except Mercury and Pluto, for times up to 10^7 years. [7] We continued to follow a comet until it either became unbound from the Sun and reached a distance of 150 AU or became a sun-grazer. We have since performed this integration again (unpublished), allowing comets to physically impact the planets. Here, I report the results of this integration.

In our forward integration 98% of the comets are removed from the solar system before the end of the integration: 91% are ejected from the solar system, 1% and .1% impact Jupiter and Saturn, respectively, and $\approx$ 6% are destroyed by becoming sun-grazers (including P/Encke). The number of sun-grazers is far greater than would be expected from the existing analytic theories and is due to the heretofore unappreciated effects of secular resonances. The median lifetime of all known short-period comets from the current time to ultimate destruction or ejection is approximately 5×10^5 years.

We found that under a classification based on period that most comets move between Jupiter-family ($P < 20$ yr) and Halley-type ($P > 20$ yr) comets many times (median of 12) in their dynamical lifetimes. For example, Figure 6 shows the dynamical evolution of the comet P/Tempel-Swift. [8] The solid curve in Figure 6a shows the evolution of the comet's semi-major axis over its entire lifetime. The top dashed line represents the boundary between the Jupiter family and the Halley type. Notice that the comet moves back and forth across this

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[7] There have been many efforts to study the dynamical behavior of the short-period comets by direct numerical integration of their orbits (Kazimirchak-Polonskaya 1967; Belyaev 1967; Carusi *et al.* 1985; Nakamura & Yoshikawa 1991; and Tancredi & Rickman 1992). However, these integrations have been limited to timescales that are much less then the dynamical lifetimes of these objects, the longest previous integration being about 4000 years.

[8] I must emphasize that this figure is only illustrative; it cannot be used to predict the long-term behavior of this particular comet because its orbit is chaotic.

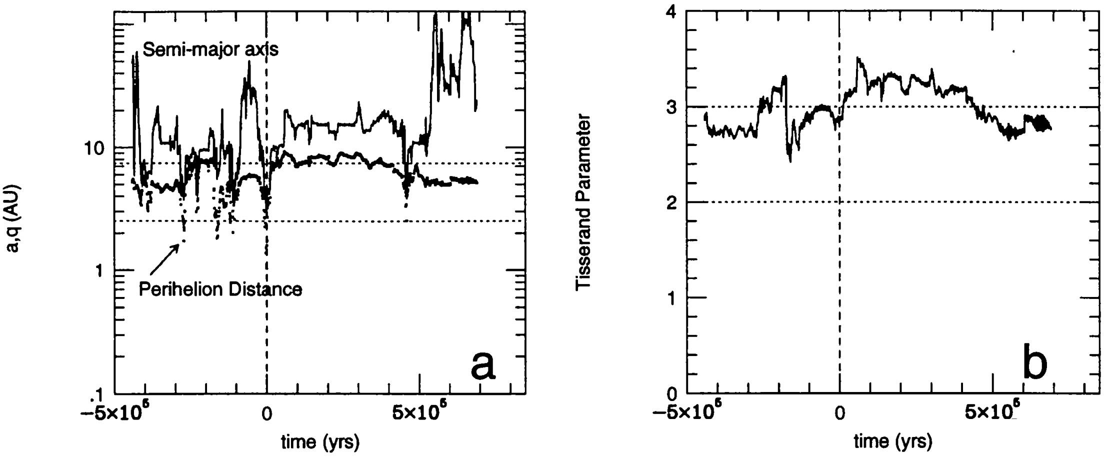

Figure 6. The behavior in our integration of the comet P/Tempel-Swift over its entire dynamical history. a) Semi-major axis (solid) and perihelion distance (dots). The top dotted line is at $P = 20$ years, the currently accepted division between Jupiter family and Halley type comets. The bottom dotted line represents the limit of visibility ($q = 2.5\,\mathrm{AU}$) set by Quinn, Tremaine, & Duncan (1990). b) Tisserand parameter. The top dotted line is at $T = 3$. Objects with T greater than this value cannot be on Jupiter-crossing orbits. The bottom dotted line is at $T = 2$, the boundary between Jupiter-family and Halley-type comets as proposed by Carusi et al. (1987a).

boundary several times, especially in the backward integration. It is interesting to note that when this comet is visible ($q < 2.5\mathrm{AU}$), it is always a member of the Jupiter family.

On the other hand, we found that 92% of all short-period comets remain in the same class of comet if the boundary between the Jupiter-family and the Halley-types is based on the Tisserand parameter as first suggested by Carusi et al. (1987a). To illustrate the effectiveness of this classification scheme, Figure 6b shows the temporal variation of T for the comet P/Tempel-Swift. Recall that their proposal is to place the boundary between the two classes at $T = 2$. Although T is not a constant, the comet does not cross the boundary. Indeed, most of the comets that cross are initially very close to the boundary — less than 2% of the comets switch from $T < 1.5$ to $T > 2.5$.

The classification scheme based on T thus appears to be clearly more dynamically meaningful than one based on the orbital period. Fortunately, only three objects are reclassified under this new system (i.e., comets P/IRAS, P/Machholz, and P/Tuttle change from the Jupiter-family to the Halley-type class in the new scheme). The power of a T-based classification lies in the fact that we find in our integrations that for most comets T is well enough conserved during their dynamical lifetimes that the vast majority of them are in the same class now as when they were first injected into the planetary region.

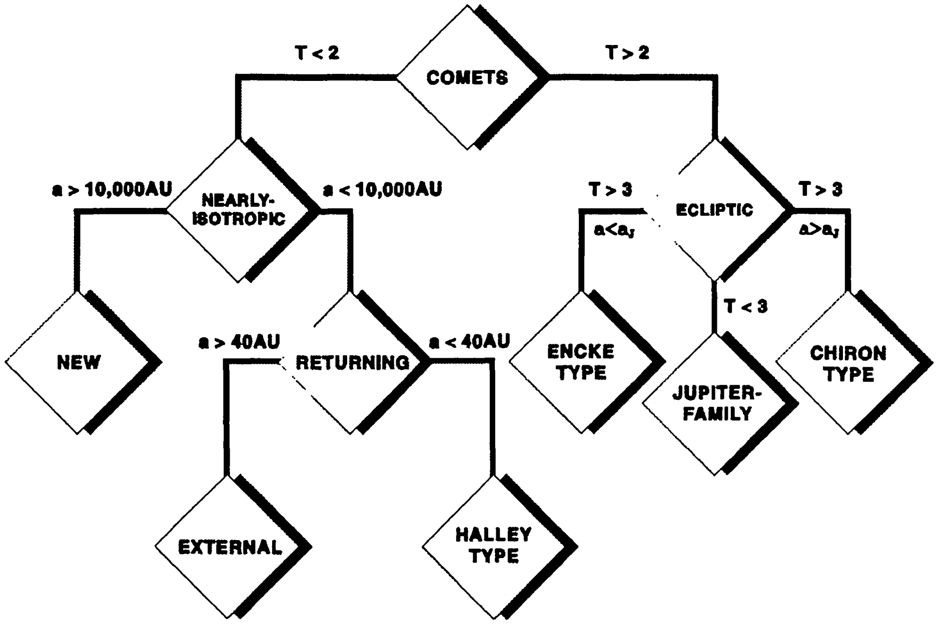

Figure 7. Proposed family tree for comets.

5. A Proposed New Classification Scheme

Based on the discussion in the last section, it appears that we should use the Tisserand parameter, T, to determine class. We are now faced with the following question: Should we adopt the currently accepted classification scheme except that we use T instead of orbital period to distinguish between the Jupiter family and Halley type? The following considerations suggest that the present scheme is unsatisfactory and that a new taxonomy is called for.

- As discussed in Section 2, the division between long-period comets and short-period comets has no physical basis.
- According to the definition of Carusi et al. (1987a), all comets with $T > 2$ and $P < 200$ years are considered to be in the Jupiter family. But P/Encke ($T = 3.03$ *but* with aphelion at 4.1 AU) and Chiron ($T = 3.35$ *but* with perihelion at 8.5 AU) fit this definition. Indeed, if $T > 3$ then a comet cannot cross Jupiter's orbits, so perhaps they should not be considered a member of the Jupiter family.
- On the other hand, P/Tempel-Swift, which is clearly currently a Jupiter-family comet, spends a considerable amount of time in an orbit which is dynamically similar to that of Chiron with pericenter closer to Saturn's orbit than Jupiter's and $T > 3$ (see Figure 6). As stated above, we would like a classification scheme where, at least at the most significant levels, comets do not change classes.

The difficulties identified in the preceding comments would be mostly eliminated by the classification scheme shown in Figure 7. The most significant division is based on the Tisserand parameter. In this scheme comets with $T > 2$

would be designated *ecliptic* comets because most members have small inclinations. Comets with $T < 2$, which are mainly comets from the Oort cloud, are designated *nearly isotropic* comets, reflecting their inclination distribution. In the last section, the results of very long orbit integrations are discussed which show that almost all comets stay in one of these classes throughout their entire dynamical lifetimes. So, this division is fairly robust and therefore dynamically significant.

Ecliptic comets can be further subdivided into three groups. Comets with $2 < T < 3$ are on Jupiter-crossing orbits and are dynamically dominated by that planet. We should call these *Jupiter-family* comets. This class has most of the same members as the Jupiter family defined by the orbital period. Comets with $T > 3$ (not Jupiter-crossing) should not be considered members of the Jupiter family. A comet that has $T > 3$ and $a < a_J$ is designated a *Encke-type*. Note that this combination of the T and a implies that the orbit of this object is entirely interior to Jupiter, i.e., the aphelion distance is less than a_J. A comet that has $T > 3$ and $a < a_J$ (orbit is exterior to Jupiter) is designated a *Chiron-type*. It is important to note that Chiron-type comets are probably the same as Centaur asteroids. The differences between an asteroid and a comet in this part of the solar system is not clear.

As with the long-period comets in our original classification, nearly-isotropic comets can be subdivided into two groups: *new* and *returning* comets. New comets have the same definition as in the previous scheme. The class of returning comets covers a much larger range than previously, from comets with $a \leq 10,000\,\mathrm{AU}$ down to three comets with periods less than 20 years. This includes all of the comets that used to belong to the old Halley-type. Grouping all these comets together is fitting since we now believe that the old Halley-type comets are captured from the old long-period comets. Thus all the comets in this group most likely had a similar origin.

Having a class as large as the returning comets may be somewhat awkward. Therefore, this class is further divided into two groups based on their dynamics. Carusi et al. (1987a, 1987b) have found that a significant fraction of returning comets with small semi-major axes are trapped (at least temporally) in mean motion resonances with Jupiter. They suggest that many of the comets that are currently not librating in such a resonance may have done so in the past or may do so in the future if their semi-major axes are small enough. In the proposed classification scheme, comets that have a small enough semi-major axis to be able to be trapped in a mean motion resonance with a giant planet are designated as *Halley-type* comets and those that have semi-major axes larger than this as *external* comets.

It is not clear, however, where to draw the boundary between Halley-type comets and external comets. The comet with the largest semi-major axis known to be librating about a mean motion resonance is P/Swift-Tuttle, with a semi-major axis of 26 AU (Carusi et al. 1987b). P/Swift-Tuttle is librating about the 11:1 mean motion resonance with Jupiter. It is not known how large a semi-major axis a comet can have and still librate about a mean motion resonance with one of the giant planets (an interesting question for future research). However, we do know of a Kuiper Belt object that is in the 3:2 mean motion resonance with Neptune, Pluto. Pluto is thus the object with the largest semi-major axis that is known to be in a mean motion resonance. Therefore, I suggest that we use Pluto's semi-major axis (40 AU) as the boundary between these two classes of comets. In this way, the new Halley-type class contains most of the same objects as the original Halley-type.

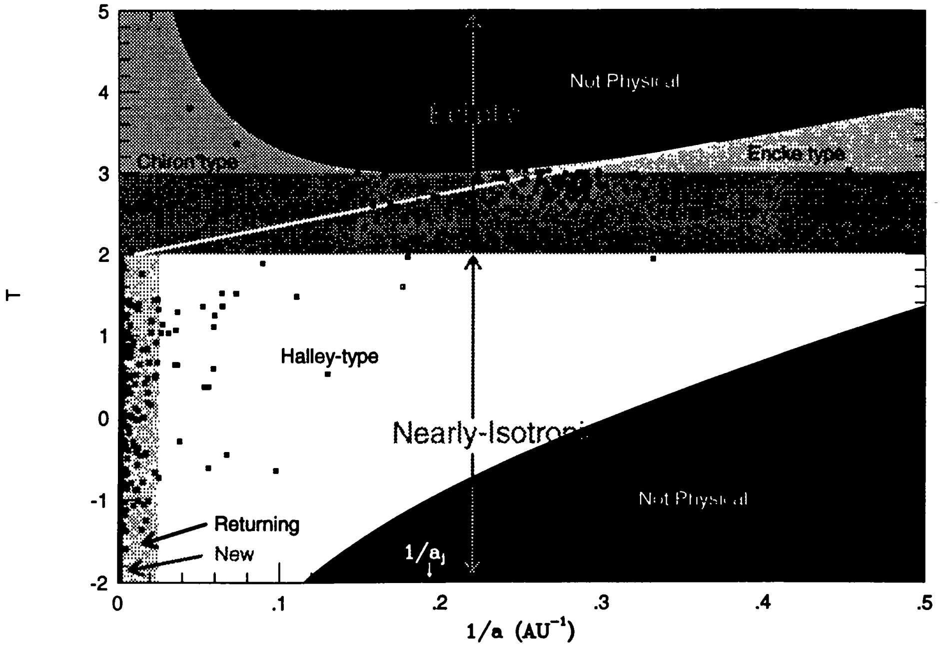

Figure 8. The location of the classes in the proposed taxonomy as a function of the Tisserand parameter (T) and semi-major axis (a). The major classes of ecliptic and nearly-isotropic comets are defined by T and are independent of a. The ranges of these two classes are thus shown with arrows only. The extent of the subclasses are shown by different shadings. Also shown is the location of all the comets with $1/a > 0$ in Marsden's catalog of cometary orbits and the location of the 3 known Centaur 'asteroids'. The white curve shows the relationship of T versus a for a comet with $q = 2.5\,\mathrm{AU}$ and $i = 0$. Comets above and to the left of this line have $q > 2.5\,\mathrm{AU}$ and thus are difficult to detect.

Figure 8 shows the location of the classes in my new scheme as a function of the Tisserand parameter and semi-major axis. Also shown is the location of all the comets in Marsden's catalog of cometary orbits (Marsden 1992). Comparing the new scheme with the numerical simulations discussed in Sections 3 and 4 we find that: *i*) Comets very rarely change their primary class (*ecliptic* versus *nearly-isotropic*) but do frequently change their subclass (ie., *new* versus *returning* or *Jupiter-family* versus *Chiron-type*). *ii*) Most nearly-isotropic comets most likely originate in the Oort cloud, while most ecliptic comets originate in the Kuiper Belt.

Finally, let us consider nearly parabolic comets in this scheme. For comets with large semi-major axes, the Tisserand parameter becomes $T \approx 2\sqrt{2q/a_J}\cos(i)$.

Thus, low-inclination objects with $4 < q < a_J$ are considered to be members of the Jupiter-family in this scheme. It is not clear whether we should classify nearly parabolic comets as members of the Jupiter family. In some ways it is appropriate in that if a typical member of the Jupiter family is scattered into an orbit with a large semi-major axis, then by this definition it would still be a member of the Jupiter family because T is approximately conserved during the encounter. For the same reason, any Oort cloud comet that is scattered into the Jupiter family by an encounter with Jupiter would have been a member of the Jupiter family before the encounter. Thus, it would seem reasonable to accept this scheme as presented and accept near parabolic, low-inclination orbits with perihelia near Jupiter's orbit to be Jupiter-family comets.

Objects on near-parabolic orbits with $q \gg a_J$ are another issue altogether. These objects would be considered ecliptic comets irrespective of their inclinations. This designation for these objects is clearly not acceptable. However, a comet like this has never been observed nor is likely to be seen, because of its large perihelion distance. Thus, it again seems reasonable to accept this scheme as presented, with its limitations, and revisit this issue in the future if such an object is discovered.

6. Chemical Abundance Considerations

In the discussions thus far, I have considered only the dynamics of comets. The only classification scheme based on chemical abundance of which I am aware is one recently developed by A'Hearn et al. (1995, see also Schleicher 1994). These authors measured the abundances of OH, CN, C_2, C_3, and NH in 41 comets. They found two distinct classes of objects.

The results of their OH, CN, and C_2 observations are shown in Figure 9a. They identified two classes of comets based on the production rates for C_2, $Q(C_2)$, and CN, Q(CN), normalized to OH, Q(OH). In the class known as *typical*, CN and C_2 vary together with respect to OH. In the *depleted* class, C_2 is depleted with respect to CN. The authors argue that this effect is unlikely to be a result of physical evolution and thus must represent differences that existed at the time that the comets formed.

Interestingly, there is a strong relationship between the taxonomy proposed by A'Hearn et al. (1995) and the new dynamical classification scheme outlined above. This relationship can be seen in Figure 9b, which plots $Q(C_2)/Q(CN)$ as a function of the Tisserand parameter. Almost all (20 out of 23) of the nearly-isotropic comets in the sample of A'Hearn et al. (1995) are classified as typical. Of the three that are not typical, one (P/IRAS) is a comet that our orbit integrations show moves across the nearly-isotropic – ecliptic boundary at $T = 2$. Conversely, 50% (9 out of 18) of the ecliptic comets are classified as typical and 50% as depleted. Schleicher (1994) explains this relationship by suggesting that there was a region in the solar nebula where the chemical abundance in the planetesimals changed. Interior to that point typical comets formed. Almost all the observed nearly-isotropic comets (presumably now originating in the Oort cloud) came from this region. External to that point, depleted comets formed. Ecliptic comets come from both regions.

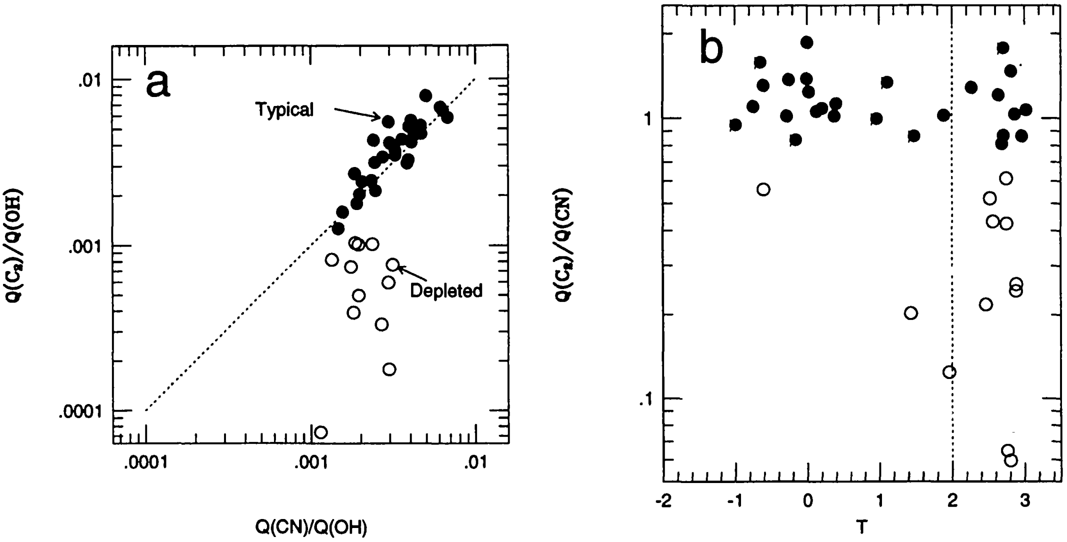

Figure 9. a) The ratio of the production rates of C_2 to OH as a function of the ratio of the production rates of CN to OH in the data collected by A'Hearn et al. (1995). Two types of comets are found: *Typical* (•) and *Depleted* (○). The line is not a fit to the data, but one that represents a ratio of unity. It should be noted, however, that the mean $Q(C_2)/Q(CN)$ for Typical comets is greater than one. b) The ratio of the production rates of C_2 to CN as a function of Tisserand parameter. The vertical line represents the boundary between ecliptic and nearly-isotropic comets.

This interpretation fits in well with the ideas concerning the origin of comets discussed in Section 3, in that we are able to construct a model for the origin and evolution of comets that is consistent with both the chemical and dynamical taxonomies. Figure 10 helps to visualize this model. When the comets condensed out of the solar nebula, there was a transition in abundance that occurred between ~ 36 AU and ~ 42 AU from the Sun. Comets closer to the Sun than this transition were typical comets, while those condensing farther away were depleted. Comets interior to ~ 36 AU have been ejected from the solar system, destroyed in an impact, or placed in the Oort cloud fairly early on in the history of the solar system. Since almost all of the nearly-isotropic comets currently come from the Oort cloud, they will in general be typical. On the other hand, most of the ecliptic comets come from the Kuiper Belt. The region of the Kuiper Belt that is currently losing comets stretches 6 AU between ~ 36 AU and ~ 42 AU from the Sun. Since we observe that the ecliptic comets are a mixture of typical and depleted comets, we can conclude that the typical-depleted transition occurred in this region of the Kuiper Belt.

The model presented in the last paragraph may not be the only valid one and may not explain all of the available data. As with the new classification scheme described above, it should be used as a straw man against which to compare our observations, simulations, and ideas.

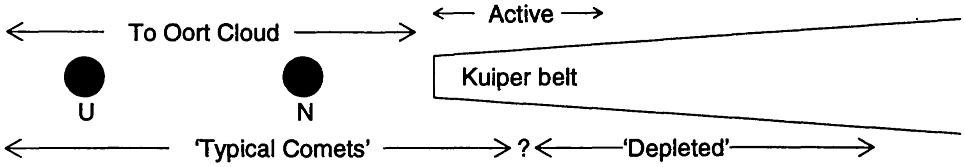

Figure 10. The current outer structure of the solar system showing the locations of Uranus (U), Neptune (N), and the Kuiper Belt. The labels at the bottom of the diagram refer to the type of comet (either typical or depleted) that formed in that region of the solar nebula. The labels above the planets refer to the dynamical history of comets that we currently see that formed in those regions. They either were placed in the Oort cloud at early epochs or are coming from the currently active region of the Kuiper Belt.

7. Concluding Remarks

The previous sections have developed a new classification scheme for comets based on our current understanding of their origin and evolution (see Figure 8). The main division between comets is defined by the Tisserand parameter, T, which is a measure of the influence of Jupiter on the dynamics of the comets. Comets with $T < 2$ tend to have a uniform inclination distribution and thus are called 'nearly-isotropic comets', comets with $T > 2$ are known as 'ecliptic comets'. Long-term dynamical integrations by Levison & Duncan (1994) have shown that over 90% of comets with periods currently less than 200 years remain in one of these two classes throughout their dynamical lifetimes. Therefore, these new classes are dynamically significant and probably reflect the source region of the comets that are members of them.

If the models discussed in Section 3 are correct (see also Quinn, Duncan, & Tremaine 1990), then most nearly-isotropic comets have come from the Oort cloud. Conversely, most ecliptic comets originated in the Kuiper Belt. As briefly discussed at the end of Section 5, however, there will be exceptions to this trend.

Nearly-isotropic comets are divided into two subclasses based on semi-major axis: 'new' and 'returning' comets. In addition, returning comets are divided into two smaller groups: 'Halley-type' and 'external'. Ecliptic comets are divided into 3 groups based on T and location in the solar system; 'Jupiter-family', 'Chiron-type', and 'Encke-type'. Long-term numerical orbit integrations show that comets can move freely between the subclasses within a main class.

The main motivation for reevaluating our cometary classification scheme was to better represent our current thinking about the origin and evolution of these objects. This does not imply, however, that the ideas and theories presented above are undisputed facts. On the contrary, one of the important purposes of a new classification scheme is to provide a framework for the evaluation of these ideas.

Acknowledgments. I would like to thank Giovanni Valsecchi, Brian Marsden, and Hans Rickman for supplying input for the new classification scheme. This new scheme reflects their ideas as much as it does mine. I am also grateful to Dave Schleicher for providing invaluable insight into his cometary taxonomy and Paul Weissman for being an excellent overall resource on this subject. Finally, I would like to thank Martin Duncan, who can occasionally be helpful.

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