

# The populations of comet-like bodies in the Solar system

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## ABSTRACT

A new classification scheme is introduced for comet-like bodies in the Solar system. It covers the traditional comets as well as the Centaurs and Edgeworth–Kuiper belt objects. At low inclinations, close encounters with planets often result in near-constant perihelion or aphelion distances, or in perihelion–aphelion interchanges, so the minor bodies can be labelled according to the planets predominantly controlling them at perihelion and aphelion. For example, a JN object has a perihelion under the control of Jupiter and aphelion under the control of Neptune, and so on. This provides 20 dynamically distinct categories of outer Solar system objects in the Jovian and trans-Jovian regions. The Tisserand parameter with respect to the planet controlling perihelion is also often roughly constant under orbital evolution. So, each category can be further subdivided according to the Tisserand parameter.

The dynamical evolution of comets, however, is dominated not by the planets nearest at perihelion or aphelion, but by the more massive Jupiter. The comets are separated into four categories – Encke-type, short-period, intermediate and long-period – according to aphelion distance. The Tisserand parameter categories now roughly correspond to the well-known Jupiter-family comets, transition types and Halley types. In this way, the nomenclature for the Centaurs and Edgeworth–Kuiper belt objects is based on, and consistent with, that for comets. Given the perihelion and aphelion distances together with the Tisserand parameter, our classification scheme provides a description for any comet-like body in the Solar system. The usefulness of the scheme is illustrated with examples drawn from numerical simulations and from the present-day Solar system.

**Key words:** celestial mechanics – comets: general – minor planets, asteroids – planets and satellites: general – Solar system: general.

## 1 INTRODUCTION

There is a need to improve the taxonomy for comet-like bodies in the Solar system. First, as a result of recent discoveries, the populations of comet-like bodies in the Solar system are known to be much more extensive than previously thought. The last decade has seen the discovery of more than 600 trans-Neptunian objects, beginning with (15760) 1992 QB<sub>1</sub> (Jewitt & Luu 1993), as well as the identification of ~100 Centaurs (e.g. Scotti 1992) to supplement the early serendipitous finding of (2060) Chiron (Kowal 1979). Moreover, many unusual objects have now been found circulating essentially within the known planetary system, for example (5335) Damocles (e.g. Asher et al. 1994) and the ‘asteroids’ (4015) Wilson–Harrington = 107P/Wilson–Harrington, (7968) Elst–Pizarro = 133P/Elst–Pizarro and (2060) Chiron = 95P/Chiron. These objects

blur the traditional clear distinction between comets and asteroids, either on physical or dynamical grounds.

Secondly, the spatial distribution of objects in orbits largely beyond Neptune, but with aphelion distances  $Q$  much less than the conventional inner edge of the dynamically active Oort cloud ( $Q \ll 20\,000$  au, say), is believed to comprise a flattened disc or belt-like structure. These objects have orbits that in some cases extend hundreds of astronomical units (au) from the Sun, and although resembling asteroids in appearance are widely thought to be cometary in composition. This trans-Neptunian zone includes the region referred to as the Kuiper or Edgeworth–Kuiper belt (EKB), and probably merges in the form of an extended trans-Neptunian disc into the inner core of the Oort cometary cloud. Trans-Neptunian objects are a possibly significant source of low-inclination ‘Jupiter-family’ comets (Quinn, Tremaine & Duncan 1990), again muddying the traditional distinction between comets and asteroids.

In fact, the Centaur population appears to represent an important link between trans-Neptunian objects and Jupiter-family comets

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(Dones, Levison & Duncan 1996; Stern & Campins, 1996; Levison & Duncan 1997). Centaur orbits are typically planet-crossing and have relatively short dynamical lifetimes ( $\sim 10^6$  yr). Chiron, which is one of a number of exceptionally large minor bodies with perihelia close to or within the orbit of Saturn, exhibits cometary activity (e.g. Luu & Jewitt 1990) and even has a periodic comet designation: 95P/Chiron. At least one recently discovered comet, namely C/2001 T4 (NEAT), has a very similar Chiron-like Centaur orbit. Taken together, the evidence suggests a picture in which comets and distant minor planets are dynamically reprocessed from one population to another, for example from the Edgeworth–Kuiper belt, through Centaurs to Jupiter-family comets, and so on. Similarly, it is possible for objects to be scattered out of the main asteroid belt and evolve into similar areas. So, it is possible that some Centaurs may be rocky or asteroidal while others may be icy or cometary. This is analogous to the examples given by Fernández, Gallardo & Brunini (2002) of mixing between the Jupiter-family and near-Earth asteroid populations, and again highlights both the difficulty of separating physically distinct populations of objects using purely dynamical characteristics, and the need for a unified dynamical classification scheme capable of describing the full range of observed orbital types.

In parallel with these observational advances, the march of computer power now ensures that the orbits of most Solar system bodies can be routinely integrated for millions of years. Given the wealth of simulation data and the diversity of new discoveries, the taxonomy of Solar system objects assumes great importance. For a classification scheme to be useful, it should allow us to place objects with similar physical or dynamical characteristics in sets, and to examine the bulk statistics of the sets in detail. However, in making sense of the complicated evolutionary pathways followed by objects such as short-period comets and Centaurs, the historical classification scheme seems obsolete. A new taxonomy should clarify the principal dynamical paths followed by different classes of object through interplanetary space, and facilitate the definition of dynamical lifetimes and the flux and transfer probabilities of objects from one dynamical class to another.

Traditionally, comets have been classified as short- or long-period according to whether their periods of revolution  $P$  are less than or greater than 200 yr. This unphysical division (Levison 1996) has frequently been justified in terms of the time over which comets have been observed with scientific precision (e.g. Weissman 2001). However, the canonical upper limit for ‘periodic’ comets has now been spectacularly broken by the return of 153P/Ikeya–Zhang with an orbital period in excess of 350 yr, and also by recent discoveries such as asteroid 2002 RP<sub>120</sub> with a period of about 420 yr.

Centaurs are conventionally defined as asteroids or cometary nuclei circulating largely between the orbits of Jupiter and Neptune and usually crossing the orbit of at least one giant planet (e.g. Jedicke & Herron 1997; Larsen et al. 2001). Jedicke & Herron’s definition restricts Centaur semimajor axes to less than that of Neptune (i.e.  $a \lesssim 30$  au), and therefore allows objects defined as Centaurs to pass significantly beyond the orbit of Neptune into the Edgeworth–Kuiper belt. A straightforward extension of this definition would allow Centaurs to be regarded simply as a continuation of the ‘scattered disc objects’, perhaps even encompassing those resonant objects that are not protected in the long term from close approaches to Neptune. The scattered disc was the name introduced by Duncan & Levison (1997) following the discovery of 1996 TL<sub>66</sub> (Luu et al. 1997) to describe a population of relatively high-inclination, high-eccentricity trans-Neptunian objects. The idea that Centaurs and the scattered disc may be drawn from the same underlying population has been

advocated recently both by Marsden (1999a) and by Emel’yanenko, Asher & Bailey (2003).

This paper introduces a new classification scheme for comet-like bodies of the Solar system. There is much evidence from previous work (e.g. Kazimirchak–Polonskaya 1972; Kresák 1972, 1980, 1983; Everhart 1977; Rickman & Froeschlé 1988; Manara & Valsecchi 1991; Dones et al. 1996; Levison 1996) that the evolution of comets and Centaurs often takes place under the control of one or another major planet, usually with near-constant aphelion or near-constant perihelion, or via aphelion–perihelion interchanges. This motivates us to consider the planets controlling the perihelion  $q$  and aphelion  $Q$  as fundamental to the classification of any comet-like bodies. There is also evidence that low-inclination objects tend to evolve inwards, whereas the reverse is true for high-inclination objects. This suggests that we use the inclination – or better still, the Tisserand parameter  $T_P$  with respect to the controlling planet – as a third criterion. The Tisserand parameter is an approximate constant of the motion, at least when the orbital perturbations are dominated by a single planet. Given the set of values ( $q$ ,  $Q$ ,  $T_P$ ), our new taxonomy provides an instantaneous classification for any comet-like body in the Solar system.

## 2 AN OUTLINE OF THE CLASSIFICATION SCHEME

### 2.1 The zone of control

The Hill radius is defined as

$$R_H = a \left( \frac{M_P}{3M_\odot} \right)^{1/3}, \quad (1)$$

where  $M_P$  is the mass of the planet,  $M_\odot$  is the mass of the Sun and  $a$  is the semimajor axis of the orbit of the planet about the Sun (e.g. Murray & Dermott 1999). It corresponds to the position of the Lagrange points in the restricted three-body problem (e.g. Arnold, Kozlov & Neishtadt 1987) and so marks the largest distance at which the planet may possess a moon. A Solar system object can be classified according to the planets which have the greatest effect at perihelion and at aphelion. For typical eccentricities, a perihelion lying 4 or 5 Hill radii beyond an inner planet is often sufficiently distant for the dynamics to be controlled by the outer planet. So, we conclude that for a planet to control an object, then the perihelion or aphelion must lie closer than a distance of  $\approx 3$  Hill radii to the orbit of the planet (see e.g. Charnoz, Thébaud & Brahic 2001).

In our classification scheme, the zone of control of each planet extends to  $3k$  Hill radii, with the parameter  $k \simeq 1$ . In this way, the Solar system is banded into concentric zones of control of first Jupiter, then Saturn, Uranus and Neptune. Over the next few million years the mean semimajor axes and maximum aphelia of the four major planets Jupiter, Saturn, Uranus and Neptune are (5.2, 5.5), (9.6, 10.4), (19.2, 20.8) and (30.1, 31.0) au, respectively (Applegate et al. 1986). Three times their Hill radii are 1.1, 1.3, 1.4 and 2.3 au, respectively. These distances provide a rough basis for estimating the respective boundaries between the zones of control. For example, for Jupiter to control the object at perihelion, the perihelion must lie between 4 and 6.6 au approximately. If the aphelion also lies in the range, then we classify the minor body as a J object. For Saturn to control the object at aphelion, then  $6.6 < Q < 12.0$  when the object is denoted by JS. We will give detailed examples shortly, but the general idea should now be obvious to the reader.

**Table 1.** Definition of the Tisserand parameter classification scheme. The boundary near  $T_P \simeq 2.8$  marks the limit above which it is impossible for an object to be directly ejected in a single encounter.

Tisserand class	Tisserand parameter
Class I	$T_P \lesssim 2.0$
Class II	$2.0 \lesssim T_P \lesssim 2.5$
Class III	$2.5 \lesssim T_P \lesssim 2.8$
Class IV	$2.8 \lesssim T_P$

## 2.2 The Tisserand parameter

The Tisserand parameter is an approximation to the Jacobi constant, which is an exact integral of motion in the circular restricted three-body problem. It is defined as (e.g. Murray & Dermott 1999)

$$T_P = \frac{a_P}{a} + 2 \cos i \sqrt{\frac{a(1-e^2)}{a_P}}, \quad (2)$$

where  $a_P$  is the semimajor axis of the planet.

Ignoring the positive orbital eccentricity of the planet, objects with  $T_P$  greater than 3 are in principle confined to regions wholly interior or wholly exterior to the orbit of the planet. There is a long history of usage of the Tisserand parameter with respect to Jupiter  $T_J$  to divide the cometary families (e.g. Kresák 1972, 1980, 1982, 1983, 1985; Vaghi 1973a,b; Carusi & Valsecchi 1987; Levison & Duncan 1994; Levison 1996). Fig. 1 shows all short-period comets in the plane of semimajor axis  $a$  and eccentricity  $e$ . The comets have been colour-coded according to their Tisserand parameter with respect to Jupiter. Motivated by these plots, we propose a four-fold division according to the Tisserand parameter as indicated in Table 1.

In our classification scheme, we use the Tisserand parameters with respect to the major planets ( $T_J$ ,  $T_S$ ,  $T_U$  and  $T_N$  with obvious notation) to classify objects for which the perihelion lies within the zone of control of the planet. So, for example, an  $SU_{IV}$  object is a minor body for which the perihelion is controlled by Saturn and aphelion by Uranus and for which the Tisserand parameter with respect to Saturn is larger than approximately 2.8. Here and henceforth, we always denote the Tisserand parameter class as a subscript.

## 3 COMETS

### 3.1 Historical introduction

Objects classified as comets display the widest variety of dynamical behaviour in the Solar system. Unfortunately, there is little or no agreement as to the precise definition of different cometary types. Historically, the major cometary division has been between those classified as ‘long-period’ ( $P > 200$  yr) and ‘periodic’ or ‘short-period’ ( $P < 200$  yr) comets (e.g. Duncan, Quinn & Tremaine 1988; Nakamura & Kurahashi 1998; Levison 1996; Crovisier 2001). The majority of the short-period group belong to the so-called Jupiter family, most of which have very short periods indeed (a mean value close to 8 yr). For this reason, the periodic comets are usually divided simply on the basis of orbital period into two classes: Jupiter-family comets with  $P < 20$  yr (e.g. Fernández 1985, 1994) and Halley-type comets with  $20 < P < 200$  yr (e.g. Carusi et al. 1987b).

Since 1999, however, one-apparition comets with periods in the range  $30 < P < 200$  yr have been given a standard cometary ‘C/’ designation, rather than the usual periodic ‘P/’ identifier (Marsden

1999b; Green 2000). The official range for short-period comets therefore now extends to only 30 yr instead of the former 200-yr limit, and comets with  $30 < P < 200$  yr are now described as ‘intermediate period’ (Marsden & Williams 1999). The principal disadvantages of this change are that one-apparition intermediate-period comets cannot be easily identified as periodic simply from their designation, while the phrase ‘intermediate period’ in fact has a rather wide range of previous connotations, having been used to describe objects with periods both in the Halley-type  $20 < P < 200$  yr range (e.g. Fernández 1980; Fernández & Gallardo 1994) and with much longer periods up to  $\sim 10^3$  yr (e.g. Everhart 1974).

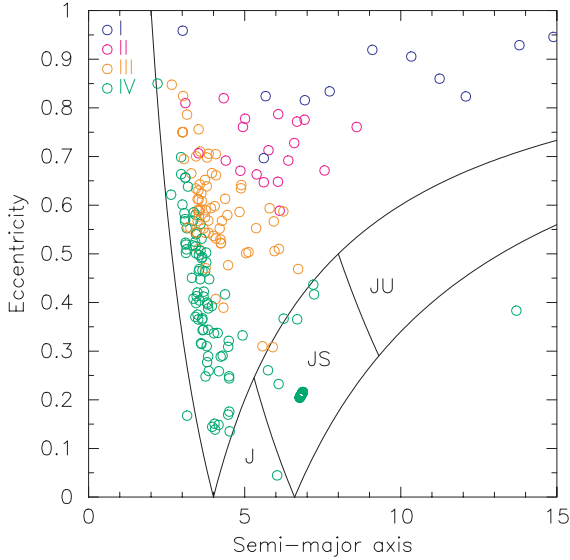
In fact, the situation is more confused still. Whipple (1978) appears to have chosen  $P = 25$  yr to separate his ‘Class V’ short-period comets (essentially the classical Jupiter family) from his Class IV intermediate-period group ( $25 < P < 1000$  yr); while Everhart (e.g. 1972, 1973) adopted 13 yr instead of 20 yr as a convenient boundary between short-period and intermediate-period comets, the latter being defined to have periods in the range  $13 < P < 1000$  yr. Others (e.g. Rickman & Froeschlé 1988; Stagg & Bailey 1989; Wetherill 1991) have instead adopted various aphelion distances  $Q$  in the range 8–10 au to distinguish Jupiter-family comets from Halley types, while a few authors (e.g. Nakamura & Kurahashi 1998) have simply considered all comets with  $P < 1000$  yr as ‘periodic’.

Contrary to the view expressed by Fernández (1994), therefore, a classification based on orbital period alone is *not* very useful. The range of definitions used by different investigators to describe essentially the same cometary subgroups appears greatly, and unnecessarily, to complicate any comparison of observational or theoretical results obtained by different authors. We hope that our historical summary has convinced the reader that there is a clear need to improve the taxonomy for comet-like bodies in the Solar system!

### 3.2 Taxonomy of comets

The zone of control of Jupiter extends between approximately 4 and 6.6 au. In our classification scheme, a ‘comet’ has a perihelion  $q < 4$  au, and so lies formally outside the zone of control of Jupiter. None the less, Jupiter dominates the lives of all the short-period comets. For example, 1P/Halley has perihelion within the orbit of Venus and aphelion just beyond the orbit of Neptune, yet Jupiter plays the most important role in its evolution (Carusi et al. 1988). We propose a fourfold division of comets with perihelion distances less than approximately 4 au, to include Encke (E), short-period (SP), intermediate-period (I) and long-period (L) types. The division is based on aphelion distance, with – as usual – further subdivision into the Tisserand parameter classes (Table 1) denoted by Roman-numeral subscripts. Further embellishments on this basic scheme could be introduced to accommodate the resonant and non-resonant main-belt asteroids (e.g. the Hildas, in the 3:2 mean-motion resonance with Jupiter) and objects on Earth-crossing or Earth-approaching orbits with periods much less than that of Jupiter, such as near-Earth objects. The approximate boundaries between the E, SP, I and L comet types are listed in Table 2.

Working outwards from the Sun, we first come to the E-type comets. These have aphelion closer to the Sun than approximately 4 au, i.e.  $Q$  within the main belt. The prototype is 2P/Encke ( $Q \sim 4.1$  au) which lies on an orbit that does not approach closer than a few Hill radii to Jupiter, making it stable within the inner Solar system for periods of time far greater than that of typical comets. (The orbit is not, however, stable for indefinitely long periods, as it is subject to long-term secular perturbations which drive the perihelion into the Sun on a time-scale of  $\sim 100\,000$  yr; see Farinella et al. 1994; Levison & Duncan 1994; Valsecchi et al. 1995 for details.) Comet



**Figure 1.** Plot of eccentricity versus semimajor axis for short-period comets in Marsden & Williams (1999). All objects are colour-coded according to their Tisserand parameter classes with respect to Jupiter. Most of the comets lie in the SP category, leftward of the  $q = 4.0$  au line. To the right of that line, the boundaries of the J, JS and JU categories are marked.

107P/Wilson–Harrington, with a similar orbit, is a largely inactive body also known as asteroid (4015), and noted by Marsden 1992 to be identical to the low-activity comet C/1949 W1 (=1949g) following Bowell’s identification of precovery observations of the asteroid on Palomar–Schmidt images. Another object, (2201) Oljato, has displayed outgassing in the past, and although currently classified as an Apollo-type asteroid could well be an evolved Encke-type comet (e.g. Weissman et al. 1989; McFadden et al. 1993). Many similar bodies in this class appear to be bona fide asteroids, rocky bodies perhaps originating via collisions in the main asteroid belt.

**Table 2.** The upper panel shows the classification scheme for comets. We define Encke-type (E), short-period (SP), intermediate-period (I) and long-period (L) comets based on perihelion and aphelion positions. The lower panel shows the scheme for objects for which the perihelion is under the control of Jupiter. The J class describes objects for which both perihelion and aphelion are under the control of Jupiter, the JS class for which the perihelion is under the control of Jupiter and the aphelion under the control of Saturn, and so on. In the final two classes, E stands for Edgeworth–Kuiper belt and T for the trans-Neptunian region immediately beyond the Edgeworth–Kuiper belt, i.e. the ‘trans-EK belt’.

Object	Perihelion	Aphelion
E	$q \lesssim 4$	$Q \lesssim 4$
SP	$q \gtrsim 4$	$4 \lesssim Q \lesssim 35$
I	$q \gtrsim 4$	$35 \lesssim Q \lesssim 1000$
L	$q \gtrsim 4$	$Q \gtrsim 1000$
J	$4 \gtrsim q \gtrsim 6.6$	$Q \lesssim 6.6$
JS	$4 \gtrsim q \gtrsim 6.6$	$6.6 \lesssim Q \lesssim 12.0$
JU	$4 \gtrsim q \gtrsim 6.6$	$12.0 \lesssim Q \lesssim 22.5$
JN	$4 \gtrsim q \gtrsim 6.6$	$22.5 \lesssim Q \lesssim 33.5$
JE	$4 \gtrsim q \gtrsim 6.6$	$33.5 \lesssim Q \lesssim 60.0$
JT	$4 \gtrsim q \gtrsim 6.6$	$Q \gtrsim 60.0$

Next we come to the SP comets, which include most objects conventionally thought of as Halley-type and Jupiter-family comets. Many authors have used the Tisserand parameter with respect to Jupiter to separate these classes. Levison (1996) suggested that comets with  $T_J < 2.0$  should be defined as Halley-types and those with  $T_J > 2.0$  should be Jupiter-family. However, the precise value of  $T_J$  separating the two types of behaviour is somewhat arbitrary and may depend on period. For example, Rickman & Froeschlé (1988) and Bailey (1992) identified a value of the order of 2.5 as a better marker of a dynamically significant separation. Rather than worry about the precise boundary between Jupiter-family and Halley-types, we use the fourfold division according to Tisserand parameter introduced in Section 2, namely, Class I with  $T_J \lesssim 2.0$ , Class II with  $2.0 \lesssim T_J \lesssim 2.5$ , Class III having  $2.5 \lesssim T_J < 2.8$  and Class IV having  $T_J \gtrsim 2.8$ . Very roughly, these can be thought of as corresponding to Halley-types, transition types, loosely bound Jupiter-family comets and tightly bound Jupiter-family comets, respectively. We call all objects with  $q < 4$  au and  $4 < Q < 35$  au short-period objects, and differentiate between objects within the SP class using the Tisserand parameter with the subclass denoted by a Roman numeral subscript. So, for example, an SP<sub>I</sub> object corresponds to a Halley-type comet under the conventional classification.

The third class consists of I-type comets, which have perihelion distances less than 4 au and aphelia between approximately 35 and 1000 au. Comets with aphelion distances of less than about 35 au frequently librate around high-order resonances with Jupiter (Carusi et al. 1987a,b; 1988; Chambers 1997) and show evidence for systematic secular changes of their orbital elements (Bailey & Emel’yanenko 1996). Recent examples of I-type comets are C/1995 O1 (Hale–Bopp) and 153P/Ikeya–Zhang. They have Tisserand parameters with respect to Jupiter of 0.879 and 0.040, respectively, and so both fall into the I<sub>1</sub> category.

The fourth class is the L-type comets, which have perihelion distances of less than 4 au and aphelia greater than 1000 au. Comets classified under the conventional system as long-period fall into either the L or the I class in our system. L-types – such as C/1910 A1 (the Great January comet) – have made no more than their first few passages through the inner Solar system. In contrast, I types are expected to have made rather more perihelion passages on average. It is sometimes useful to subdivide L-types into new and young (e.g. Fernandez 1981; Wiegert & Tremaine 1999; Horner & Evans 2002). New comets, with  $a \gtrsim 10\,000$  au, are first time entrants to the Solar system from the Oort Cloud.

We are of course aware that many comets display activity beyond 4 au from the Sun, and similarly that there is an increasing number of known objects with perihelion distances beyond 4 au that have been classified as active comets (e.g. C/2002 V2 [LINEAR] and C/2003 A2 [Gleason]) or which have distinctly cometary orbital characteristics (e.g. 2002 VQ<sub>94</sub>). We seek to develop a coherent classification scheme that is useful for all comet-like bodies in the Solar system.

From now on, as we move outwards in perihelion, we are able to exploit the idea that comet-like bodies lie under the control of the giant planets. After the ‘comets’, the next class of objects we encounter are those for which perihelion lies within the zone of control of Jupiter. In the conventional scheme, these bodies are still classified either as Jupiter-family comets, or as asteroids if they show no outgassing. In our picture, the designations are listed in Table 2. Here, and henceforth, our classification scheme proceeds with the first letter designating the planet controlling the perihelion

and the second letter designating the planet controlling the aphelion or the region in which the aphelion lies. The Tisserand parameter is defined with respect to the planet which controls the perihelion. So, for instance, a  $JN_{IV}$  object has a perihelion under the control of Jupiter, an aphelion between 22.5 and 33.5 au and so under the control of Neptune, and a Tisserand parameter with respect to Jupiter  $\gtrsim 2.8$ ; while a  $JE_{III}$  type has an aphelion between 33.5 and 60 au and so lying in the Edgeworth–Kuiper belt and a Tisserand parameter with respect to Jupiter in the range 2.5–2.8.

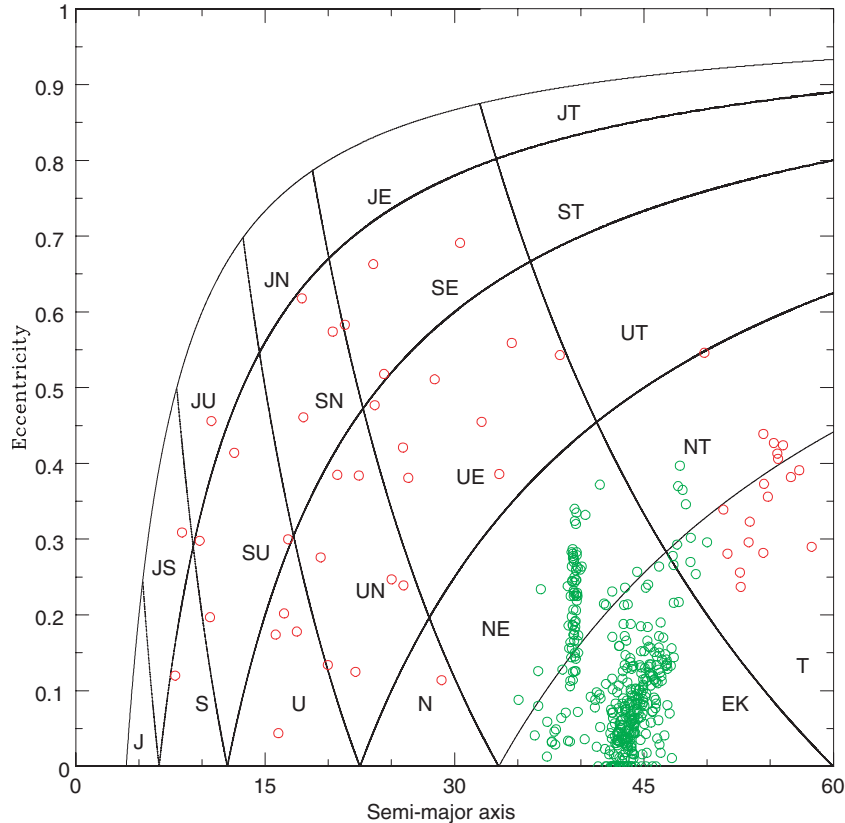
An example of a  $J_{IV}$  object is 29P/Schwassmann-Wachmann 1, which has a near-circular orbit just beyond Jupiter. Its Tisserand parameter is  $T_J = 3.0$  and so it is not quite Jupiter-crossing. The object itself is unusual in a couple of respects. The low eccentricity of its orbit coupled with its unusually great size ( $\sim 20$  km radius) allows it to be followed with ease through its entire orbit. It undergoes regular outbursts, with its visual magnitude rising from its usual 17 (at perihelion) by a number of magnitudes, reaching as high as 10 at its brightest.

An example of a  $JS_{IV}$ -type object is 39P/Oterma. It was originally discovered in 1942 orbiting in a Hilda-type 3:2 mean-motion resonance with Jupiter, with a low-eccentricity orbit and a period of a mere 8 yr. At that time, its orbit lay between those of Mars and Jupiter and it would have been classified as an  $SP_{IV}$  comet in our picture (although clearly as a resonant ‘Hilda’ in a more complete scheme). However, it was later noted that it had entered the 3:2 resonance in 1937 from the 2:3 resonance, and returned to the 2:3 in 1963 (e.g. Kazimirschak-Polonskaya 1972). Continuous periods in any one resonance are short owing to the unstable nature

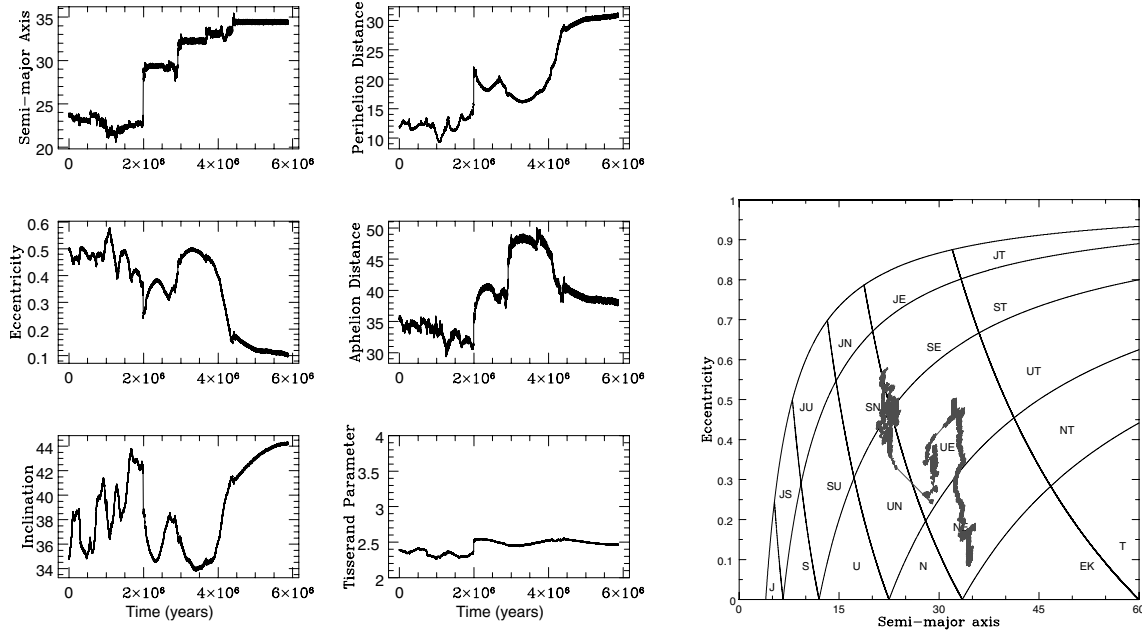
of the orbit, but it is noteworthy that  $T_J \simeq 3.0$  was approximately conserved during this evolution. The present orbit lies outside that of Jupiter, with a current perihelion distance of 5.46 au and an aphelion of 9.02 au. This object seems to be a good example of a recent ‘handing down’ of a Centaur from the control of Saturn to Jupiter, with further periods as an SP comet seeming quite probable. Finally, recent discoveries such as C/2002 A1 (LINEAR) and C/2002 A2 (LINEAR), with semimajor axes close to that of Uranus, furnish examples of  $JN_{III}$  objects.

### 3.3 Resonances

A key feature of the orbital evolution of Centaurs and many other comet-like objects in the outer Solar system is the tendency for the semimajor axis to lie close to one or another mean-motion resonance with a planet. This behaviour is exemplified by the so-called Plutinos (objects in the 2:3 mean-motion resonance with Neptune, i.e. around  $a \sim 39.5$  au), which appear clearly in Fig. 2, and also by the evolution of 2000 FZ<sub>53</sub> shown in the top left-hand plot of Fig. 3. The occurrence or otherwise of a long-lived resonance will clearly affect the transfer probability from one part of the  $(q, Q, T_p)$  phase space to another and is an important consideration in the dynamical evolution of outer Solar system objects. There are recently discovered objects with semimajor axes close to essentially all the significant Neptunian resonances, from 1:1 [e.g. 2001 QR<sub>322</sub> and 2002 PN<sub>34</sub>] to 1:8 [e.g. (54520) 2000 PJ<sub>30</sub>]. However, detailed discussion of the classification and role of such resonances is beyond the scope of this paper.



**Figure 2.** Plot of eccentricity versus semimajor axis showing the boundaries of the classification scheme. The red circles are listed as Centaurs and scattered disc objects by the Minor Planet Center, while the green circles are Edgeworth–Kuiper belt members. In both cases, we only record objects if their observed arcs are 30 d or more.



**Figure 3.** The evolution of dynamical quantities for a clone of the Centaur 2000 FZ<sub>53</sub>. The left-hand panel of plots shows the variation of semimajor axis, perihelion, aphelion, eccentricity, inclination and Tisserand parameter (in this case with respect to Uranus) against time in years. The rightmost plot (available in colour in the online version of the journal on *Synergy*) shows the evolution in the plane of semimajor axis and eccentricity, with the different categories of the classification scheme marked. The clone spends most of the first 1 Myr as a UE object and ends in the NE category. Notice the very sharp transition from UN to UE object at  $\sim 2$  Myr. (Starting orbital elements of the clone are  $a = 23.595$  au,  $e = 0.497$ ,  $i = 34.865^\circ$  at JD 245 1120.5.)

#### 4 CENTAURS AND TRANS-NEPTUNIAN OBJECTS

Table 3 gives the classification scheme for objects under the control of giant planets other than Jupiter. As before, the notation is that the first letter designates the planet controlling the perihelion and the second letter denotes the planet controlling the aphelion or the region in which the aphelion lies. So, a UN object has a perihelion controlled by Uranus and an aphelion controlled by Neptune, and so on. The letters EK denote objects with perihelia and aphelia lying close to or within the classical Kuiper or Edgeworth–Kuiper belt. Trans-EK belt or T objects, on the other hand, may have much larger

**Table 3.** Object classification for the trans-Jovian region. The first letter designates the planet controlling the perihelion, the second letter the planet controlling the aphelion or the region in which the aphelion lies, with the final two classes EK and T being beyond all the giant planets. (S = Saturn, U = Uranus, N = Neptune, EK = Edgeworth–Kuiper belt, T = trans-EK belt).

Object	Perihelion	Aphelion
S	$6.6 \lesssim q \lesssim 12.0$	$Q \lesssim 12.0$
SU	$6.6 \lesssim q \lesssim 12.0$	$12.0 \lesssim Q \lesssim 22.5$
SN	$6.6 \lesssim q \lesssim 12.0$	$22.5 \lesssim Q \lesssim 33.5$
SE	$6.6 \lesssim q \lesssim 12.0$	$33.5 \lesssim Q \lesssim 60.0$
ST	$6.6 \lesssim q \lesssim 12.0$	$Q \gtrsim 60.0$
U	$12.0 \lesssim q \lesssim 22.5$	$Q \lesssim 22.5$
UN	$12.0 \lesssim q \lesssim 22.5$	$22.5 \lesssim Q \lesssim 33.5$
UE	$12.0 \lesssim q \lesssim 22.5$	$33.5 \lesssim Q \lesssim 60.0$
UT	$12.0 \lesssim q \lesssim 22.5$	$Q \gtrsim 60.0$
N	$22.5 \lesssim q \lesssim 33.5$	$Q \lesssim 33.5$
NE	$22.5 \lesssim q \lesssim 33.5$	$33.5 \lesssim Q \lesssim 60.0$
NT	$22.5 \lesssim q \lesssim 33.5$	$Q \gtrsim 60.0$
EK	$33.5 \lesssim q \lesssim 60.0$	$Q \lesssim 60.0$
T	$33.5 \lesssim q \lesssim 60.0$	$Q \gtrsim 60.0$

aphelion distances, and (perhaps depending on their perihelion distances) may be stable ‘outer’ objects as described by Emel’yanenko et al. (2003), or dynamically active objects similar to those conventionally known as scattered disc objects. Both EK and T classes have perihelia beyond the control of Neptune (33.5 au) but less than the conventional outer edge of the Edgeworth–Kuiper belt ( $\sim 60$  au). They differ in that the aphelion  $Q$  is less than approximately 60 au for the former and greater than 60 au for the latter. As for the comets, the information on the zone of control must be supplemented with the Tisserand parameter with respect to the controlling planet to give a complete classification. The Tisserand parameter class is given as a subscript. It is interesting to note the recent discovery of several high-inclination Centaurs, for example 2002 VQ<sub>94</sub> and 2002 XU<sub>93</sub>, which we classify as ST<sub>I</sub> and UT<sub>I</sub>, respectively.

The first Centaur discovered, (2060) Chiron, has a perihelion distance of 8.4 au and an aphelion of 18.8 au. It is classified as an SU<sub>IV</sub> object, as its Tisserand parameter  $T_S = 2.9$ . This is one of the largest Centaurs and is active at perihelion. Hahn & Bailey (1990) showed that the orbit of Chiron is rapidly evolving and that it may have been a short-period comet in the past, and will probably become one again in the future. The second Centaur discovered, (5145) Pholus, has a perihelion of 8.7 au and an aphelion of 32.1 au, together with a Tisserand parameter  $T_S$  of 2.6. It is classified as an SN<sub>III</sub> object. The orbit of Pholus is also unstable with a characteristic lifetime of  $\sim 10^6$  yr. As another example, (10199) Chariklo has a perihelion of 13.1 au which is just within the control of Uranus and an aphelion of 18.6 au. Its Tisserand parameter with respect to Uranus is 2.9, making its classification U<sub>IV</sub>. The orbit of Chariklo is more stable than either that of Chiron or Pholus, as the dynamical lifetime is roughly a factor of 10 times longer. Not all orbits in this part of the Solar system are evolving. For example, Holman (1997) found that a few low-eccentricity objects between 24 and 27 au ( $\sim 0.3$  per cent of an initial low-eccentricity primordial sample) may survive for 4.5 Gyr without significant dynamical evolution. These objects lie

in the  $N_{IV}$  class. Others (e.g. 2001 QR<sub>322</sub>, also classified as  $N_{IV}$ ) are recognized as long-lived Neptune–Trojans (Marsden 2003), and it is probably only a matter of time before similar examples of Trojans are confirmed around Uranus as well.

Almost all the known Centaurs lie within the Tisserand parameter classes III and IV. There are only a few exceptions – for example, 2000 FZ<sub>53</sub> has a Tisserand parameter with respect to its controlling planet (Uranus) of 2.4. However, the nearly isotropic influx from the Oort Cloud must inevitably produce at least a few high-inclination Centaurs. Hence, the other classes are needed, and their apparent emptiness at present is largely a selection effect.

Fig. 2 shows the plane of semimajor axis and eccentricity. The red circles show the current location of the 52 objects listed as Centaurs and scattered disc objects in 2002 June by the Minor Planet Center.<sup>1</sup> A further 16 objects lie at semimajor axes too great to be seen on the plot. These objects were chosen from the full list of Centaurs by requiring the observable arc to be greater than 30 d. Objects with shorter arcs are excluded as their orbits often change substantially from the original estimates when the arc is extended. The known population depends both on the true numbers in the various regions and on discovery selection effects. Orbits under the control of Uranus and Neptune are expected to be more long-lived than those under the control of Saturn and Jupiter. However, this is counterbalanced by the fact that objects nearer the Sun are more easily discovered. The question can be studied further by modelling the efficiency of observational surveys (Jedicke & Herron 1997). For the present Centaur population, there is a suggestion in Fig. 2 of a substantial population in the UE category. These may be being scattered down from planet to planet having originated in the Edgeworth–Kuiper belt.

The green circles in Fig. 2 show the current classification of those 373 objects with arcs greater than 30 d belonging to the Edgeworth–Kuiper belt. Again, our data were downloaded in 2002 June from the Minor Planet Center.<sup>2</sup> The two most populous categories are NE and EK. The Plutinos, a population of objects trapped in the 2:3 mean-motion resonance with Neptune (e.g. Jewitt & Luu 1996), fall into either the NE or EK category depending on eccentricity. The resonance acts to prevent close approaches to Neptune, although it is unlikely that such a mechanism would generally protect all the objects from eventual encounters with Neptune over time-scales comparable to the age of the Solar system. The EK category contains most of what are conventionally called the ‘classical’ Kuiper or Edgeworth–Kuiper belt population, while the T category contains most of what are conventionally called scattered disc objects. These last two classes can be further subdivided (Emel’yanenko et al. 2003).

## 5 NUMERICAL EXAMPLES

We now illustrate the usefulness of the classification scheme with some examples drawn from a suite of numerical simulations. Clones of the current Centaur population are integrated in the forward and backward direction for up to 6 Myr using the hybrid integrator in the MERCURY program (Chambers 1999). The orbits are integrated under the gravitational effects of the Sun and the four major planets only. The time-step is 120 d. Once objects passed beyond 1000 au, their orbits are no longer followed.

### 5.1 From UE<sub>II</sub> to NE<sub>II</sub> object

Fig. 3 shows the evolution of a clone of 2000 FZ<sub>53</sub>. For most of the first 1 Myr its perihelion is under the control of Uranus and its

aphelion lies in the Edgeworth–Kuiper belt. The Tisserand parameter with respect to Uranus is  $T_U = 2.4$ . The clone starts off as an SE<sub>II</sub> object and moves rapidly into the UE<sub>II</sub> zone.

During the course of the simulation, the clone is driven gradually towards a stable orbit with perihelion close to Neptune (an NE object). This illustrates one route by which an object can approach the Edgeworth–Kuiper belt from the Centaur region. There are two sharp transitions visible in Fig. 3. The first change, at 2.0 Myr from UN to UE, is caused by a close encounter at aphelion with Neptune; the second, at 2.9 Myr within the UE category, is caused by an encounter at perihelion with Uranus. At the end of the 6-Myr simulation, the object has a perihelion just beyond the orbit of Neptune, a high inclination and a low eccentricity. The value of its Tisserand parameter with respect to Neptune is  $T_N = 2.4$ . The orbit is similar to those of a number of objects currently residing in the inner regions of the Edgeworth–Kuiper belt, such as 1999 CP<sub>133</sub>.

The stability of the semimajor axis towards the end of the 2000 FZ<sub>53</sub> simulation suggests that it lies in a mean-motion resonance with Neptune. This is borne out by calculation of the orbital period of the clone, which is  $\sim 202$  yr, suggesting that the object probably lies in the 4:5 mean-motion resonance with Neptune (period  $\sim 164$  yr). It is possible that the orbit will continue to drift outward and stabilize after the end of the simulation, illustrating a rather rare example of outward rather than inward evolution. The ultimate destiny of such an object may therefore be to join the Edgeworth–Kuiper belt or the region beyond it.

### 5.2 From SU<sub>IV</sub> object to SP<sub>IV</sub> comet

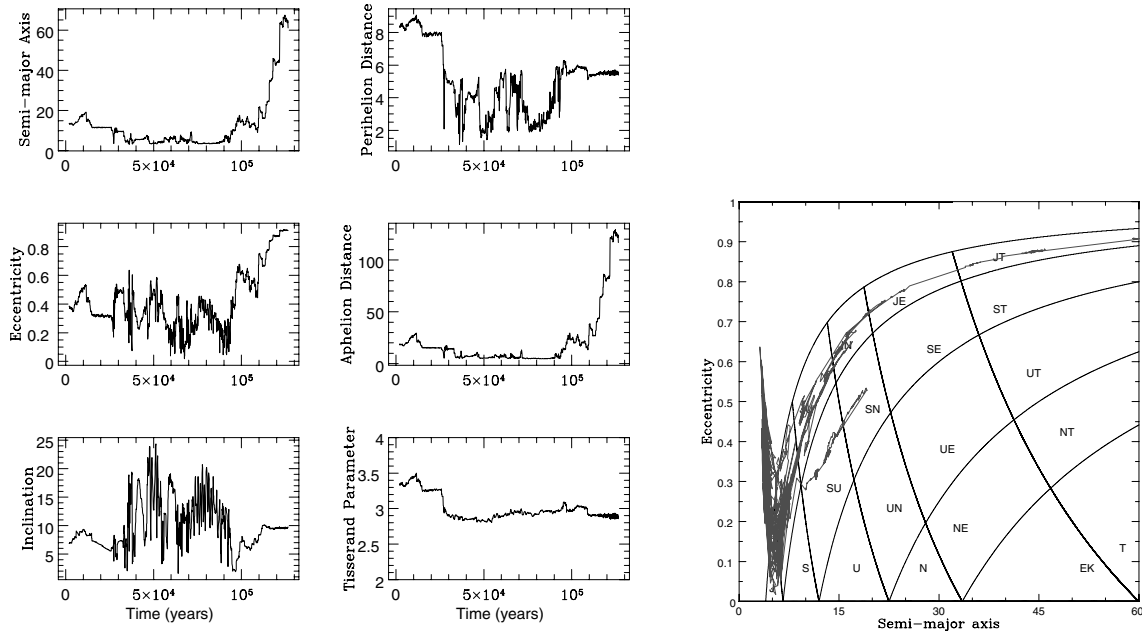
Fig. 4 shows the evolution of a clone of Chiron (cf. Hahn & Bailey 1990). This object illustrates one of the supply routes for the short-period comets. The clone starts with its perihelion under the control of Saturn, but its aphelion wanders between the control of Saturn, Uranus and Neptune, respectively, for the first  $2 \times 10^4$  yr. After this, the clone falls under the control of Jupiter through a succession of aphelion–perihelion interchanges. The Tisserand parameter  $T_J$  falls below 3 and the clone spends the next part of its lifetime ( $\sim 7 \times 10^4$  yr) as a short-period comet before leaving the SP region. This is longer than the typical fading time ( $\sim 1.2 \times 10^4$  yr) for Jupiter-family comets found by Levison & Duncan (1997). It is noteworthy that this 200-km diameter object has a significant probability of evolving to an orbit with perihelion distance less than that of the Earth (Hahn & Bailey 1990). This emphasizes the potential significance for the inner solar system of so-called ‘giant’ comets and their disintegration products when time-scales of the order of  $10^5$  yr or more are considered (e.g. Napier 2001). From the characteristic shape of the trajectory in the rightmost panel of Fig. 4, we see that the evolution proceeds along lines of roughly constant perihelion or aphelion both before and after the object comes under the control of Jupiter. The part of the life of a clone when it is controlled by Jupiter is characterized by it being highly chaotic and showing rapid dynamical evolution.

Note that the clone starts with a Tisserand parameter with respect to Saturn  $T_S = 2.9$ . During its lifetime as a short-period comet, its Tisserand parameter with respect to Jupiter  $T_J = 2.8$ . Just as in our previous example, the Tisserand parameter with respect to the controlling planet is nearly preserved during the whole evolution.

The fact that the clone stays in an area in which it will be active as a comet for such a long time suggests that cometary bodies can be captured into the inner Solar system for long enough to have a reasonable chance of decoupling from Jupiter, whether by non-gravitational forces such as outgassing (cf. Kresák 1982; Harris &

<sup>1</sup> <http://cfa-www.harvard.edu/iau/lists/Centaurs.html>

<sup>2</sup> <http://cfa-www.harvard.edu/iau/lists/TNOs.html>



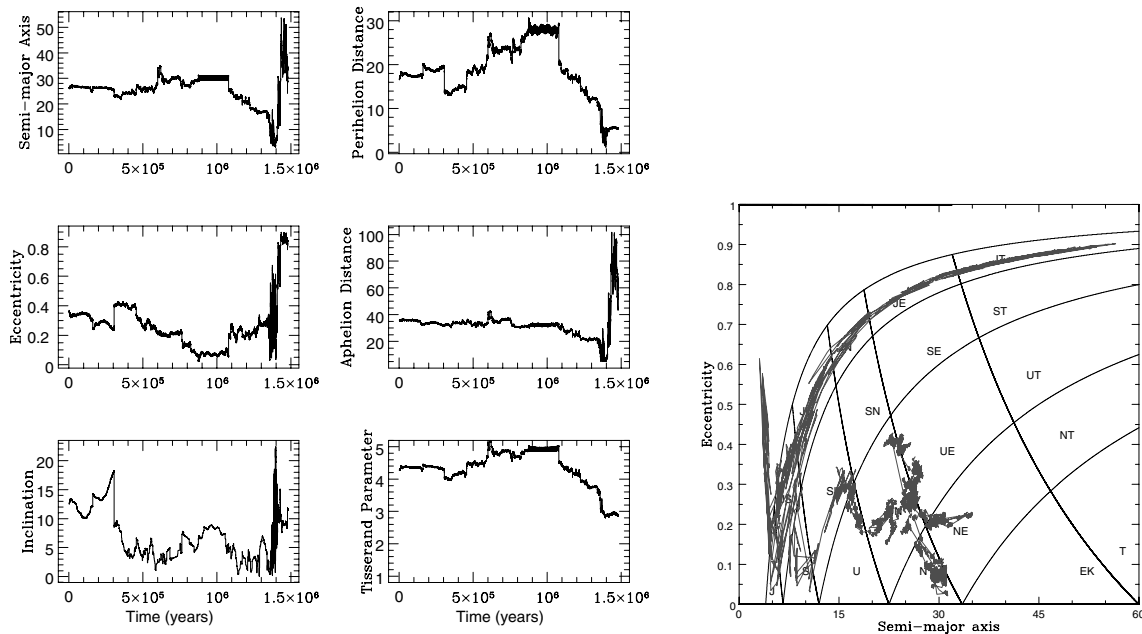
**Figure 4.** The evolution of dynamical quantities for a clone of Chiron. The Tisserand parameter plotted here is that with respect to Jupiter. The clone starts as an SU object, evolves into a short-period Jupiter-family comet and then is finally ejected from the Solar system. Notice how evolution often proceeds along lines of almost constant aphelion or perihelion in the rightmost panel. (Starting orbital elements of the clone are  $a = 13.599$  au,  $e = 0.384$ ,  $i = 6.879^\circ$  at JD 245 1220.5.) The rightmost plot is available in colour in the online version of the journal on *Synergy*.

Bailey 1998; Asher, Bailey & Steel 2001) or collisional mechanisms. Integrations occasionally provide examples of Encke-type orbits evolving to become Jupiter-family short-period comets, but the reverse evolution by gravitational means is so rare that it has never been seen (Carusi & Valsecchi 1987). It is interesting to note that the stability of an orbit approaching Saturn is lower than one approaching merely Uranus or Neptune. Similarly, an orbit in the vicinity of Jupiter is yet more unstable. This adds weight to our argument that classifying all objects in the trans-Jovian region merely

as ‘Centaur’ is insufficient to explain the full richness of dynamical behaviour in the region.

### 5.3 From $UE_{IV}$ object to $SP_{IV}$ comet

Fig. 5 shows the evolution of a clone of 1998 TF<sub>35</sub>. It starts off as a UE object with Tisserand parameter  $T_U = 2.9$ . This object is of interest since it passes through a number of different categories (UE, UN, NE, N, U, SU and S) before finally becoming a short-period



**Figure 5.** The evolution of dynamical quantities for a clone of 1998 TF<sub>35</sub>. The Tisserand parameter plotted here is that with respect to Jupiter. The clone starts as a UE object, evolves into a short-period Jupiter-family comet and then is ejected from the Solar system. (Starting orbital elements of the clone are  $a = 26.412$ ,  $e = 0.369$ ,  $i = 12.564^\circ$  at JD 245 1220.5.) The rightmost plot is available in colour in the online version of the journal on *Synergy*.



comet and then suffering ejection from the Solar system. Generally, it moves through the categories sequentially rather than frequently jumping back and forth between classes. The clone begins in an orbit influenced both by Neptune and Uranus, and distant encounters provide gradual perturbations for most of its lifetime. Eventually, encounters with Neptune move the object into a near-circular orbit controlled only by that planet. This period of evolution ends with a close encounter which moves the perihelion of the clone back to the control of Uranus. The perihelion drops further until the object encounters Saturn, at which point it is rapidly handed down to the control of Jupiter, where it becomes a short-period comet for a brief time ( $\sim 10^4$  yr) before being ejected from the Solar system. Whilst a short-period comet  $T_J = 2.9$ , so there is again excellent conservation of the Tisserand parameter with respect to the controlling planet.

#### 5.4 Comets Lagerkvist–Carsenty and Jäger

As a final example, let us consider two objects conventionally classified as short-period Jupiter-family comets, namely P/1997 T3 (Lagerkvist–Carsenty) and P/1998 U3 (Jäger). Numerical integrations by Lagerkvist et al. (2000) showed that both objects suffered recent close encounters with Saturn that drastically changed their orbits. Fig. 6 shows the evolution of the orbits of both comets over the last century. Comet Lagerkvist–Carsenty started out as an  $S_{IV}$  object in 1900 January. A close encounter with Saturn in 1954 October transferred its osculating elements through almost instantaneous SN and SE phases into its present  $JS_{IV}$  orbit. This proceeded through a perihelion–aphelion interchange, with the old perihelion becoming the new aphelion. In contrast, Comet Jäger started as an  $S_{III}$  object in 1900 January and underwent a direct transition to its present  $SP_{II}$

orbit in 1991 July. The evolution proceeded at nearly constant aphelion, as can be deduced both from the plot of the orbit and from its evolutionary track in the plane of semimajor axis and eccentricity. In this case, the close approach caused the Tisserand parameter class to change, with the controlling planet switching from Saturn to Jupiter.

## 6 CONCLUSIONS

The main aim of the paper is to introduce a new classification system for comet-like bodies. Minor bodies between Saturn and Neptune are often described simply as ‘Centaur’ and those beyond Neptune simply as ‘Kuiper belt objects’. This is not very enlightening as the histories and fates of such bodies may be very different. For example, simulations show that some Centaurs are in long-lived and stable orbits, whereas others are dynamically highly active and will evolve rapidly.

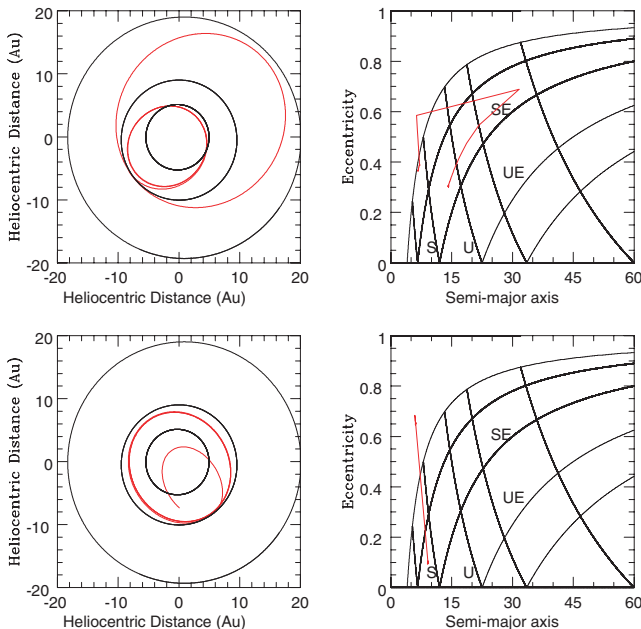
The main focus of this paper has been on the Centaurs and short-period comets. Our proposition is to classify the comet-like objects beyond Jupiter according to the planets that control the evolution of their perihelion and aphelion. For example, an SN object has a perihelion under the control of Saturn and an aphelion under the control of Neptune, while a UE object has a perihelion under the control of Uranus and an aphelion in the Edgeworth–Kuiper belt. This provides 20 dynamically distinct categories of outer Solar system objects in the Jovian and trans-Jovian regions. The evolutionary tracks of bodies such as Centaurs often show periods in which the aphelion or perihelion distances are individually rather well conserved, or encounters in which the old perihelion becomes the new aphelion or vice versa (‘perihelion–aphelion interchanges’).

The objects with smaller perihelion distances, which we designate as ‘comets’, are dominated by Jupiter and not by the planets nearest at perihelion or aphelion. In our scheme, comets have a perihelion distance of less than 4 au. They are subdivided into Encke-type, short-period, intermediate-period and long-period according to aphelion distance. Following a succession of authors beginning with Kresák (1972), we favour further subdivisions based on the Tisserand parameter. Specifically, we subdivide the categories of comets into: Class I which has  $T_J \lesssim 2.0$ , Class II which has  $2.0 \lesssim T_J \lesssim 2.5$ , Class III having  $2.5 \lesssim T_J < 2.8$  and Class IV having  $T_J \gtrsim 2.8$ . Very roughly, these can be thought of as corresponding to Halley-types, transition types, loosely bound Jupiter-family comets and tightly bound Jupiter-family comets, respectively. This idea is then extended to all comet-like bodies by identifying the Tisserand parameter of the planet controlling the perihelion with a subscript.

Given the aphelion and perihelion distance, together with the Tisserand parameter of the planet controlling the perihelion, it is straightforward to find the instantaneous classification of any Solar system object. Our new classification scheme extends the existing taxonomy for comets to cover all comet-like bodies in the Solar system.

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**Figure 6.** The evolution of comets P/1997 T3 (Lagerkvist–Carsenty), upper panels, and P/1998 U3 (Jäger), lower panels. On the left, the numerically integrated orbit is shown together with the orbits of Jupiter, Saturn and Uranus. On the right, the evolution of the comet in the plane of semimajor axis and eccentricity is presented. We have suppressed some of the labels to reduce notational clutter. Note that P/1997 T3 shows a perihelion–aphelion exchange on transference from the Saturn dominated régime to Jupiter family. For comet Jäger, the evolution proceeds through the encounter at almost constant aphelion.

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