LOW VELOCITY ENCOUNTERS OF MINOR BODIES WITH THE OUTER PLANETS

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Previous studies of close encounters of minor bodies with Jupiter have shown that the perturbations are stronger either if the encounter is very deep or if the velocity of the minor body relative to the planet is low. In the present research we investigate the effects of low velocity encounters between fictitious minor bodies and the four outer planets. Two possible outcomes of this type of encounter are the temporary satellite capture of the minor body by the planet, and the exchange of perihelion with aphelion of the minor body orbit. Different occurrence rates of these processes are found for different planets, and the implications for the orbital evolution of minor bodies in the outer Solar System are discussed.

INTRODUCTION

Close encounters with the outer planets were shown to be one of the most important factors determining the orbital evolution of those comets which move entirely within the planetary region by the classical studies of Kazimirchak-Polonskaya (1967) and Belyaev (1967). They integrated the motion of many short-period comets for a time span of 400 years, and found that encounters especially with Jupiter and Saturn caused drastic changes of the cometary orbits. Using fictitious objects, Kazimirchak-Polonskaya (1972) showed that also Uranus and Neptune could have an important effect on those orbital evolutions.

In fact, cometary orbits of this type are called "chaotic" (Oikawa and Everhart, 1979; Everhart, 1979, 1982), since they can pass through various orbital forms, such as unstable

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Trojans, horseshoes, generalized Trojans and horseshoes of some planets, Chiron type orbits, short-period cometary orbits, temporary satellite captures and others (Everhart, 1973, 1979). The entrance into, and the exit from, any of these types of motion are caused by an encounter with a major planet. Chiron is presently in a typical chaotic orbit (Everhart, 1979): its motion has been studied by Kowal et al. (1979), by Oikawa and Everhart (1979) and by Scholl (1979). The two latter studies, in particular, showed that encounters with Saturn and, to a lesser extent, with Uranus play the major role in the evolution of Chiron's orbit, which will likely evolve into an orbit typical of short-period comets in about 10^5 years.

Even if the motion of many different objects in chaotic orbits has been integrated over such time spans, a better knowledge of these orbits is needed in order to obtain a reliable quantitative description of the evolution of comets into short-period orbits. A key point appears to be the knowledge of all the possible outcomes of planetary close encounters, with the relative a priori probabilities, given certain ranges of initial conditions.

Here we will concentrate on two types of events which can occur when the relative velocity at the encounter is low: temporary satellite capture of the minor body, and transformation of its orbit from outside to inside that of the planet or vice-versa. The data that we will use for the discussion come from a numerical research on close encounters with the outer planets described in Carusi and Valsecchi (1982c). In essence, 1000 fictitious minor bodies were followed during a single close encounter with each outer major planet; thus, a total of 4000 close encounters have been computed and stored on magnetic tape. The initial orbits are chosen so as to span a wide range of initial conditions. The form of the distributions is identical for the four populations having encounters with the four outer planets, except for a scaling factor multiplying the 1/a distributions. The initial distribution functions of e and i were:

$$P(e)=\sin(\pi e) \quad \text{for} \quad 0<e<1$$

$$P(i)=\sin(6i) \quad \text{for} \quad 0°<i<30°$$

The whole intervals of variation of e and i were divided in 40 classes, and for each class of eccentricity a flat distribution in 1/a between the limits:

$$\frac{1+e}{q-R} > \frac{1}{a} > \frac{1-e}{Q+R}$$

was generated, where q and Q are the planet's perihelion and aphelion distances, and a and e refer to the minor body; R is 2/3 AU for Jupiter (as in the previous research), Saturn, Uranus, and 4/3 AU for Neptune. In order to take into account the lack of low eccentricity short-period comets of high inclination, an additional constraint was added, namely:

$$i < 2.4^\circ + 80.8^\circ e$$

This condition gives a line that roughly divides, in the e-i plane, the region populated by known short-period comets from the empty one.

The values of ω and Ω were chosen at random between 0° and 360° and it was then checked if the resulting orbits had a minimum distance from the planet's orbit of less than R. If not, they were discarded and replaced by new orbits also conforming to the given constraints. The initial values of the true anomalies were chosen with the same procedure used in Carusi and Pozzi (1978a), moving the planet and the minor body backwards, along their unperturbed orbits, from the point of minimum distance to a relative distance of 4R.

Each sample was named using the first three letters of the name of the corresponding planet; each object of a sample was identified with a number. So, JUP 393 is a fictitious object having an encounter with Jupiter, and URA 802 one having an encounter with Uranus.

TEMPORARY SATELLITE CAPTURES

The subject of temporary satellite captures (TSC) of minor bodies by the planets has received some attention, especially in connection with the origin of some natural satellites (e.g. the retrograde satellites of Jupiter, Saturn and Neptune) and with the orbital evolution of objects in chaotic orbits, like comets and meteoroids (Everhart, 1982). It is generally agreed upon the statement that definitive satellite captures, either in the restricted or the general 3-body problem, are impossible without the help of a dissipative mechanism (see, e.g., Pollack et al., 1979). Therefore, in the framework of purely gravitationally interacting mass-points, we are concerned with satellite captures only of the temporary type; in fact, they have been found in many investigations on the orbital evolution of real and fictitious short-period comets (Chebotarev, 1967; Kazimirchak-Polonskaya, 1972; Everhart, 1973; Dvorak, 1976; Carusi and Pozzi, 1978b; Rickman, 1979).

In most of the cases cited above, Jupiter has been the planet involved; in all of them the gravitational model was either a n-body or an elliptical 3-body problem. The use of a planar, circular restricted 3-body model, as done for example by Horedt (1976), Hayashi et al. (1977) and Heppenheimer and Porco (1977), often leads to results different from those obtained with the more realistic models cited above (Everhart, 1973; Carusi et al., 1979).

Systematic work on TSC's of minor bodies by Jupiter has been presented in Carusi et al. (1979) and Carusi and Valsecchi (1979, 1980, 1981). It was shown that TSC's are more likely to occur when the pre-encounter orbit of the minor body is nearly tangent to that of the planet; in this case, because of the high value of the Tisserand invariant of such orbits, a low velocity of the minor body relative to the planet may be expected, leading more easily to the satellite capture. It was also shown that in a sample composed by the majority of the short-period comets with Tisserand invariant (relative to Jupiter, and in jovian semiaxis units) greater than 2.9, 7 out of 22 underwent a TSC in the last 120 years. Most of these captures, when the trajectories of the comets were plotted in a frame centred on Jupiter and rotating with its instantaneous orbital angular velocity, were found to be simple fly-bies, although one of the comets (P/Gehrels 3) made a complete revolution about the planet during its 7 years long TSC occurred between 1967 and 1974 (Rickman, 1979; Rickman and Malmort, 1981, 1982; Carusi and Valsecchi, 1979, 1981, 1982b).

Depending on the duration of the TSC, more or less complicated planetocentric orbital patterns of the small body may be expected. Carusi et al. (1981a,b, 1982) have given a first look into this problem, starting from the orbit on which P/Oterma moved before its 1937 encounter with Jupiter, and using also, for comparison, some fictitious model objects. Other studies of this type seem necessary in order to understand more deeply the phenomena occurring at close encounters, including TSC's.

So far we have spoken of TSC's using implicitly the definition of them given in Carusi and Valsecchi (1979, 1981, 1982a,b,c): the minor body is a temporary satellite if its planetocentric orbital elements are elliptical for some time during an encounter. This is essentially the definition used by Kazimirchak-Polonskaya (1972), Everhart (1973) and Dvorak (1976); Rickman and Malmort (1982), however, require in addition that a planetocentric orbit, from pericentre to pericentre, is to be completed by the minor body, and that the motion in a planetocentric elliptical orbit has to last for at least 1000 days.

In the present investigation we have used for comparison, together with the data referred to in the Introduction, also some of the cometary evolutions described in Carusi and Valsecchi (1981, 1982a). The number of TSC's found in our samples of fictitious objects are (Carusi and Valsecchi, 1982c): 46 in JUP, 16 in SAT, 4 in URA and 4 in NEP.

Some qualitative information can be obtained plotting the values of the heliocentric and planetocentric energies of the minor bodies, computed from the osculating orbits, for a time span including the encounter (Carusi and Valsecchi, 1982 b). This is especially true since in such a plot the relative influences of the Sun and of the planet on the motion of the small body can be easily recognized. Therefore we analyzed the motion of all the objects undergoing a TSC in any of our four samples, drawing for each of them a figure, like Figs. 1 and 2, composed of the trajectory in the rotating planetocentric frame plus the energy plot just described.

About 2/3 of the TSC's found in JUP and SAT, and all of those found in URA and NEP, turned out to last considerably less than the total duration of the interaction. The period spent with elliptical planetocentric parameters appeared in those cases as a minor, and almost incidental, part of the planet-dominated orbital evolution. A typical example of this type of satellite capture is the object JUP 63, shown in Fig. 1.

On the other hand, the remaining 1/3 of the TSC's found in the samples JUP and SAT appear much more interesting. Although a clear-cut distinction from those that we have just

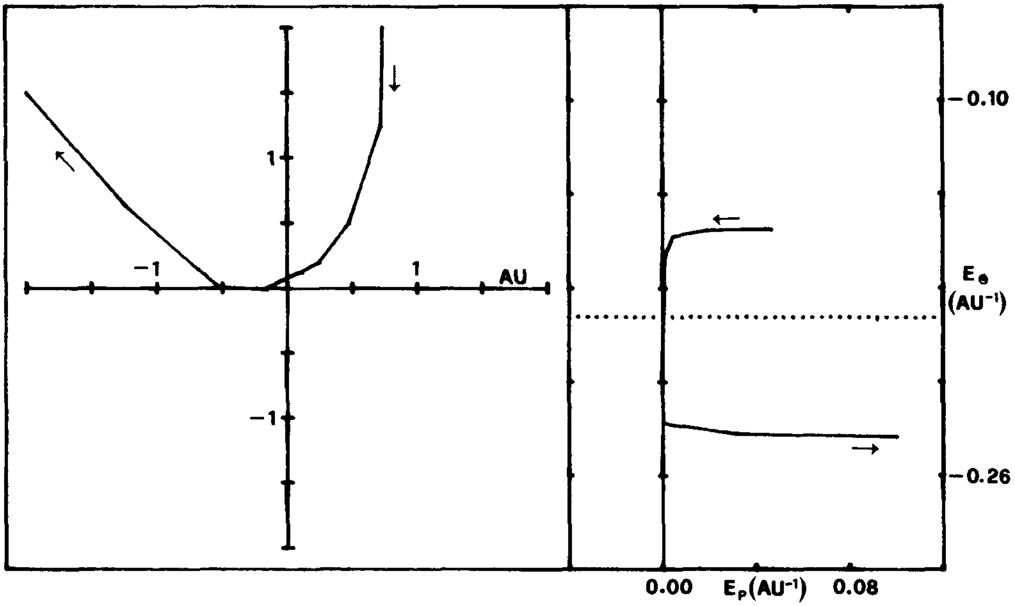

Fig. 1 - Left: ecliptic projection of the planetocentric path followed by JUP 63 in a rotating frame with the Sun on the negative x-axis.

- Right: energy plot of the evolution of JUP 63; $E_\odot = -1/a_\odot$, $E_p = -m_p/(m_\odot a_p)$ ($m_\odot$, m_p: masses of the Sun and the planet; $a_\odot$, a_p: heliocentric and planetocentric semiaxes of the minor body). Arrows show the direction of motion.

discussed cannot be made, this second type of TSC's is characterized by the fact that all, or almost all, the planetocentric motion is bound. Figure 2 shows an example, the object JUP 105; its trajectory in the energy plot resembles that of comet P/Oterma (see Carusi and Valsecchi, 1982b, Fig. 2), and in fact this comet, together with comet P/Gehrels 3, represents the best example of TSC of a short-period comet known so far. Carusi et al. (1981b) and Rickman and Malmort (1981, 1982) have examined the effects of varying one or more orbital parameters of the pre-encounter orbit (for P/Oterma) or the post-encounter one (for P/Gehrels 3): in both cases, among the varied orbits, some have been found that lead to long lasting (more than 50 years) TSC's. It is conceivable that also in the vicinity of the orbits of those objects in JUP and SAT undergoing these deeper and longer captures of the second type such long lasting satellite evolutions can be found. An example of an object of the sample SAT undergoing a TSC of the second type is shown in Fig. 3.

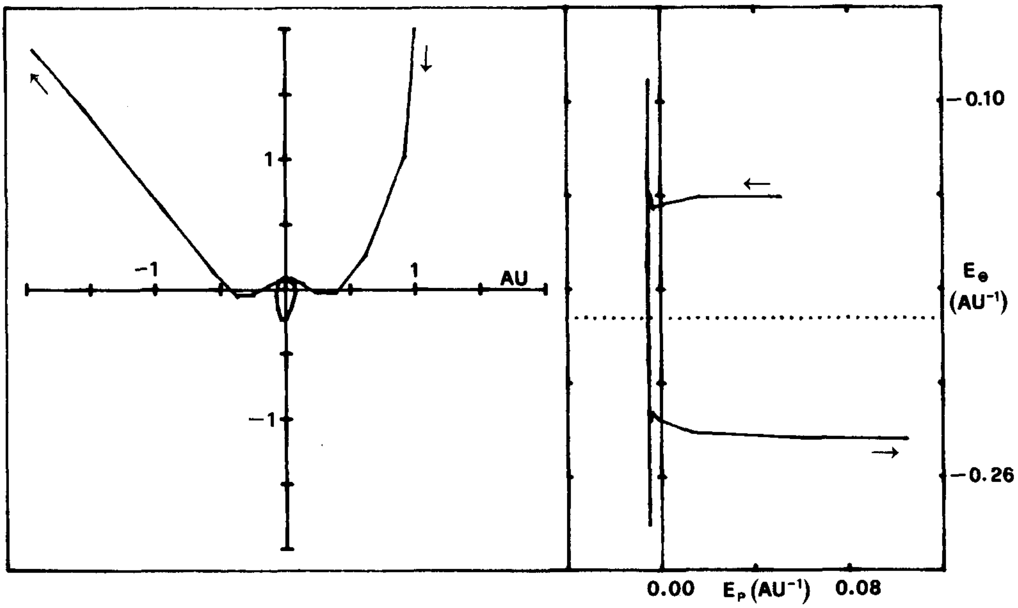

Fig. 2 - Same as Fig. 1 for the object JUP 105.

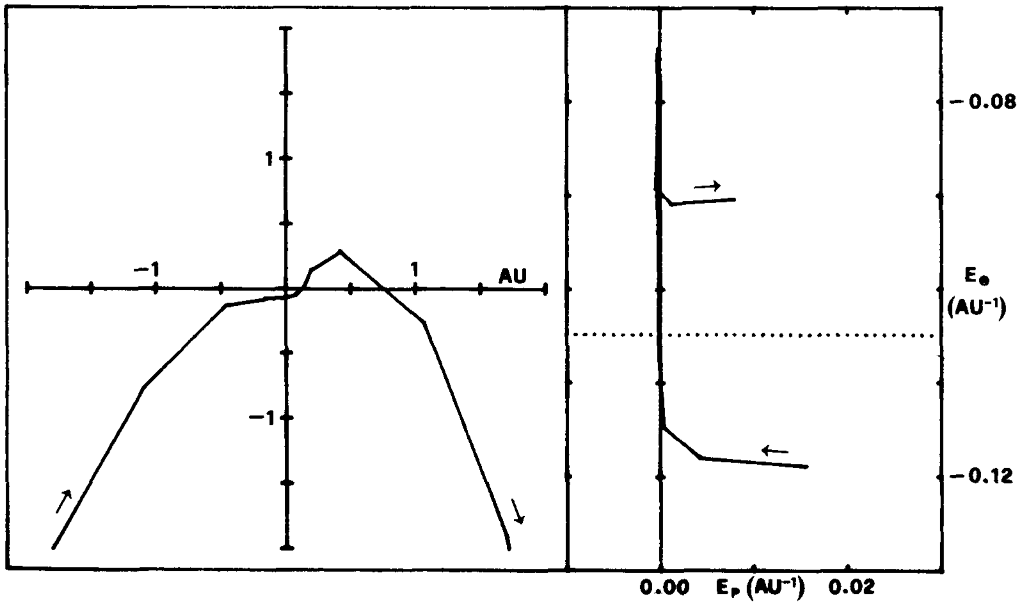

Fig. 3 - Same as Fig. 1 for the object SAT 33.

We can compare these results, relative to fictitious objects, with the findings regarding short-period comets. Carusi and Valsecchi (1981) reported 11 cases of TSC by Jupiter shared among 7 comets, within the last 120 years. Of them, 3 are of the second type (the one of P/Gehrels 3 between 1967 and 1974, and the two consecutive ones of P/Oterma between about 1935 and 1965; see Figs. 1 and 2 in Carusi and Valsecchi, 1982b), in rough agreement with the proportion found for the fictitious objects. Two examples of captures of the first type of real short-period comets, showing also rather interesting patterns in the energy plot, are given in Figs. 4 and 5.

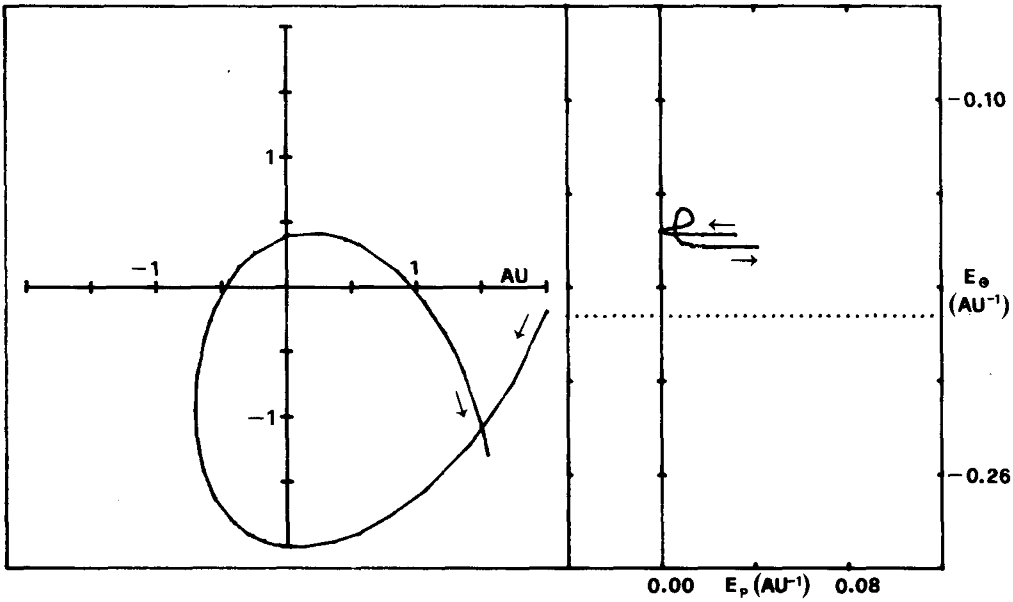

Fig. 4 - Same as Fig. 1 for the 1946-1954 encounter of P/Kowal with Jupiter.

Let us return to the question of the definition of TSC given by Rickman and Malmort (1982). Of their two additional requirements, one is rather general, and is that the small body has to perform a complete revolution about the planet; the second, the minimum duration of the bound motion of at least 1000 days, is related to captures by Jupiter, since that time lenght is roughly the period of a jovian satellite having semimajor axis of about 0.2 AU, and longer minimum du-

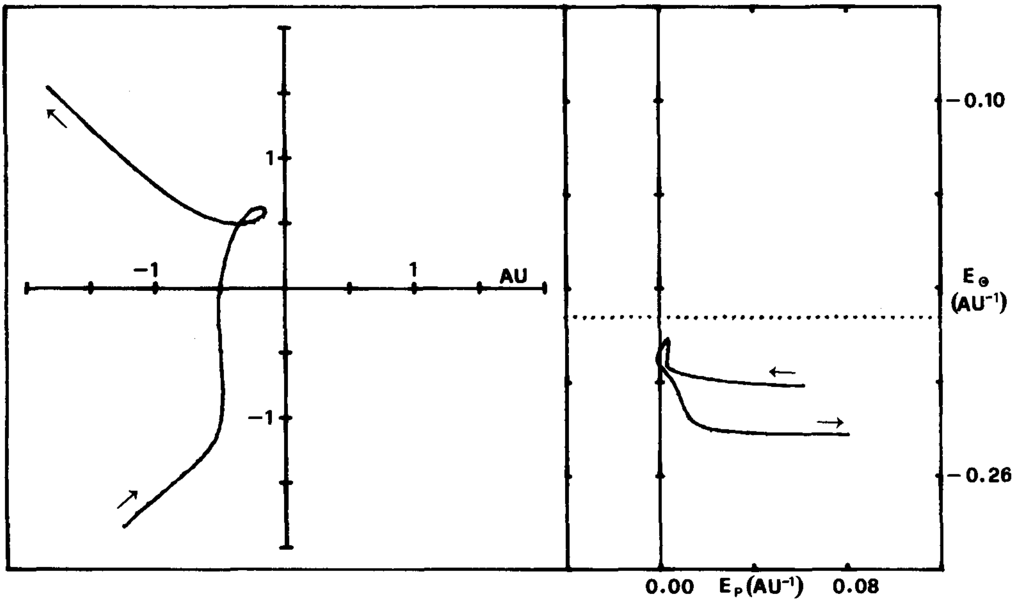

Fig. 5 - Same as Fig. 1 for the 1875-1885 encounter of P/Gunn with Jupiter.

rations should be applicable to planets less massive and more distant from the Sun. It appears that only some of the TSC's of the second type can meet these conditions, the duration of the "incidental" ones like that of Fig. 1 being too short. Satellite captures like those of P/Oterma and P/Gehrels 3 are not equivalent, according to Rickman and Malmort; however these two comets exhibited a similar behaviour in the energy plot, and the finding by Carusi et al. (1982) of a jovicentric orbital pattern of a "varied" P/Oterma very similar to the "true" P/Gehrels 3 shows that the TSC's of these two comets are to be considered as equivalent; it was only by chance that the "true" P/Oterma did not perform a complete revolution, and a definition of TSC according to which these two comets are not both temporary satellites seems a bit artificial. We suggest that, if any further refinement of the definition has to be done, starting from the simple one that has been used by the majority of the researchers, it should rather take into account the behaviour of the minor body in the energy plot.

The initial conditions leading to TSC's of the second type discussed are rather restrictive both in the case of encounters with Jupiter and with Saturn. Table I gives the approximate widths of the "capture zones" of the two types of TSC for JUP and SAT, and of the first type, the only one found, for URA and NEP. The pre-encounter orbits, as well as the post-encounter ones, are of low inclination, of high Tisserand invariant and of small to moderate eccentricity; the "capture zones" for the TSC's of the first type shrink considerably passing from Jupiter to Saturn, and decrease even much more for Uranus and Neptune.

Table I: Ranges of initial and final orbital parameters for the TSC's found in the present research.

		T	a_p/a	e	i max
JUP	first type	2.82-3.06	0.46-1.41	0.03-0.52	17°
	second type	2.98-3.04	0.66-1.38	0.03-0.33	7°
SAT	first type	2.97-3.02	0.76-1.29	0.03-0.26	8°
	second type	2.98-3.02	0.81-1.27	0.01-0.23	4°
URA	first type	2.99-3.00	0.89-1.11	0.01-0.07	6°
NEP	first type	2.99-3.00	0.89-1.11	0.01-0.08	5°

We do not find TSC's of the second type in URA and NEP because the corresponding "capture zones" are very small (likely, they are smaller than those for TSC's of first type, as for Jupiter and Saturn) and due to the limitations of our samples, they are presumably not populated enough. Therefore a more specific study of TSC's of minor bodies by Uranus and Neptune requires samples of, say, 100 at least initial orbits confined in the region of the phase space given in Table I; also satellite captures of the second type should then be found in such samples.

In a study on the limits of stability of the outer jovian satellites Hunter (1967a,b) published the final heliocentric orbital elements of those fictitious satellites that had escaped from the jovian system. Table II has been compiled from Tables I and II of Hunter (1967b), and is to be compared to the second row of Table I, which contains the TSC's of the second type found in JUP.

Table II: Ranges of final heliocentric elements of escaped jovian satellites found by Hunter (1967b).

T	a_p/a	e	i max
3.00-3.07	0.56-1.41	0.03-0.40	5°

An indirect confirmation that the phenomena connected with TSC's are essentially the same for the various outer planets, the difference being in the suitable initial conditions, is given by the fact that in the examination of the 70 captured objects of this research the main conclusions of the study of orbital patterns of minor bodies at close encounters with Jupiter by Carusi et al. (1982) were confirmed: the basic types of planetocentric trajectories were found to be essentially the same described by Carusi et al.; no hyperbolic ejection after a TSC was found because of the high value of the Tisserand invariant; reduction of the minimum distance of approach below the "unperturbed" value, that is the value obtained if the minor body orbit were not modified by the planet, was found in the majority of cases.

The implications of the previous considerations for the possibility of satellite captures of real short-period comets can be summarized in this way:

a) the initial conditions required for TSC's become more and more restrictive as we proceed outwards from Jupiter to Neptune; the probability of finding a comet temporarily bound to a planet at any given time of course depends on the still unknown density of comets in the appropriate regions of the phase space given in Table I;

b) Table I helps to understand why Carusi and Valsecchi (1981) found several TSC's among the short-period comets with T greater than 2.9; also the second type TSC's of P/Oterma and of P/Gehrels 3 are in agreement with Table I;

c) on the other hand, a similar research among real short-period comets looking for TSC's by Saturn is almost hopeless: no comets of those listed in Marsden's Catalogue (Marsden, 1979) meet the requirements, although P/van Houten would only need a somewhat less eccentric orbit, its T and i being in the acceptable range.

It must be added to point c) that some of the orbits of comets in the "trans-jovian belt" (Kresák, 1972) meet the requirements of Table I for TSC's by Saturn; the problem is that the integrations backwards, before the transferring encounter with Jupiter, are rather unreliable over long time spans (Pittich, 1981), rendering the initial conditions of possible encounters with Saturn very uncertain. The present probable orbit of comet P/Oterma (Marsden and Roemer, 1982) is within the limits of Table I for TSC's both by Jupiter and by Saturn, a dynamical characteristic unique in the whole sample of known short-period comets.

EXCHANGES OF PERIHELION AND APHELION

To study this process, in the samples JUP, SAT, URA and NEP all the objects that, as a consequence of the encounter, changed their semimajor axis from one greater than that of the planet to one smaller, or vice-versa, were identified and individually examined. They amounted to 117 in JUP, 57 in SAT, 11 in URA and 17 in NEP. Fig. 6 shows all these objects in a -1/a,e diagram in which each of them is represented by a straight line connecting its initial and final orbital elements; the initial orbit, moreover, is denoted by a black dot. The dotted lines enclose the regions of the diagram in which encounters with a specific planet, if not prevented by inclination, orientation of the orbit or libration mechanisms, can occur.

The figure discloses many interesting features of the processes that we are considering. First of all, notice the small displacements of objects on orbits with initial and final semimajor axes very close to that of the corresponding planet and moderate eccentricity. The interactions of these objects do not seem very interesting, since they do not imply substantial orbital transformations.

Much more interesting are all the other interactions. We can notice that their number increases very much passing from the two outermost planets to Saturn and then to Jupiter, and that the range of suitable initial conditions increases accordingly. From previous studies of close encounters of minor bodies with Jupiter (Carusi and Valsecchi, 1982b) we know that the interaction with the planet is stronger either if the minimum approach distance, along the unperturbed initial orbit, is very small, or if the relative velocity at the

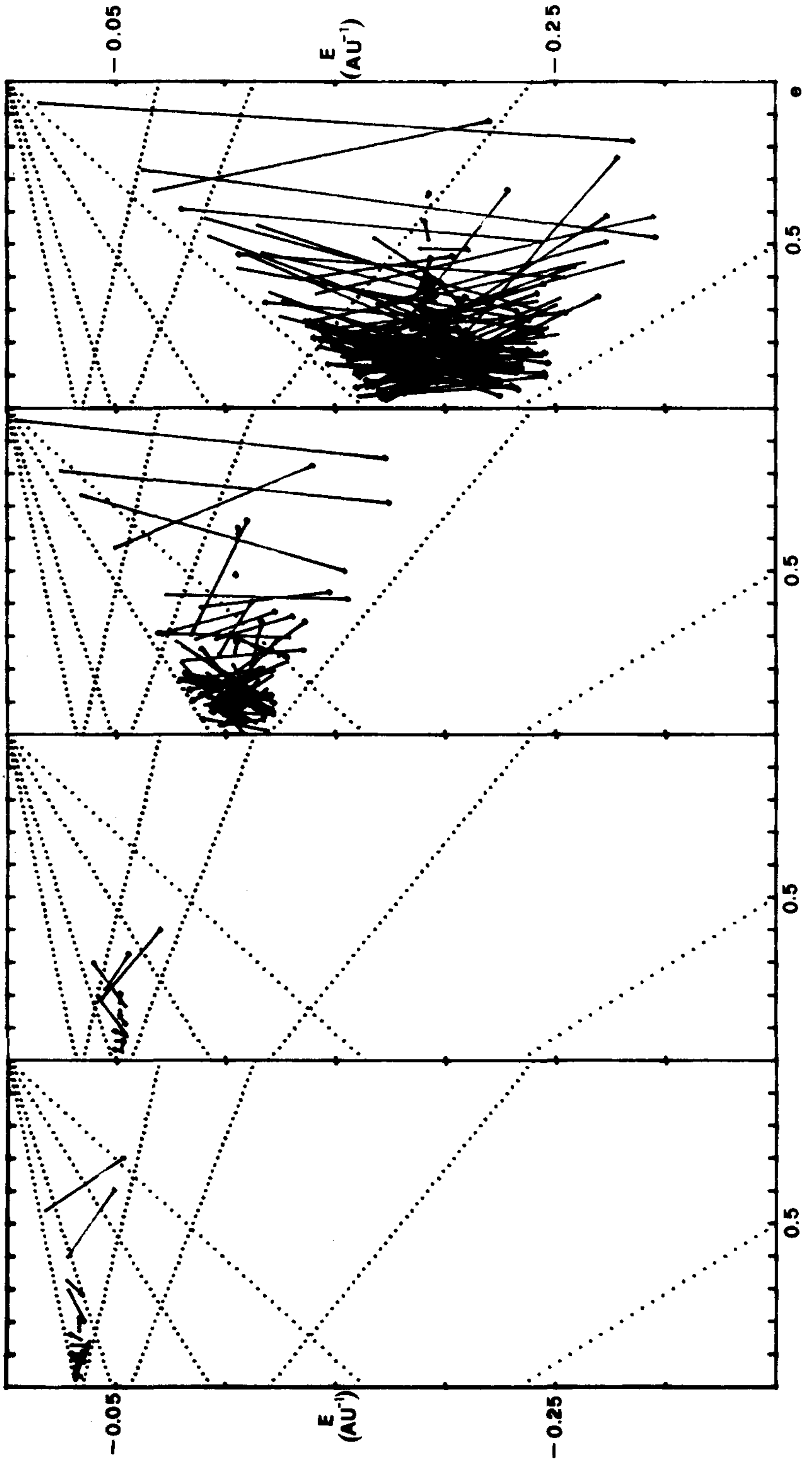

Fig. 6 - Each of the four boxes is a $-1/a,e$ diagram in which the pairs of dotted lines enclose the ranges of semimajor axis and eccentricity allowing close encounters with the corresponding planet; the uppermost pair refers to Neptune, the lowermost to Jupiter. Straight lines connect initial and final orbits of minor bodies encountering the planets (see text); dots denote the initial orbits. From left to right: encounters with Neptune; with Uranus; with Saturn; with Jupiter.

encounter is low. The first condition involves, in a complex way, all the orbital parameters of the planet and of the minor body; on the other hand, a good and simple way to check the second condition is to look at the value of the Tisserand invariant $T=1/a+2\sqrt{a(1-e^2)}\cos i$, where a is in units of the planet semimajor axis. A value of T close to 3 is typical of objects that can have encounters at low or very low relative velocity (Carusi and Valsecchi, 1982a).

Both the types of encounter have their representatives in Fig. 6; notice how many objects, as a consequence of a strong interaction, are transferred into regions in which one or more other planets can take the control of the object or, conversely, how many objects are subtracted to the control of other planets.

When the encounter velocity is very low it is possible that the pre-encounter orbit of the minor body does not cross the post-encounter one. This process requires an initial orbit nearly tangent to that of the planet; the ranges of orbital parameters of the cases that we have found in the present research are reported in Table III. These orbital transformations are a special case of the "transitions", defined by Carusi et al. (1982) as being exchanges of perihelion with aphelion or vice-versa, as a consequence of the close encoun-

Table III. Ranges of initial and final orbital parameters for the non-intersecting transitions found in this research.

	T	a_p/a	e	i max
JUP	2.93-3.03	0.48-1.40	0.03-0.52	15°
SAT	2.97-3.02	0.74-1.29	0.00-0.28	8°
URA	3.00-3.00	0.94-1.01	0.03-0.03	4°
NEP	2.99-3.00	0.95-1.15	0.03-0.14	4°

Note that the values for URA correspond to the only case found in that sample.

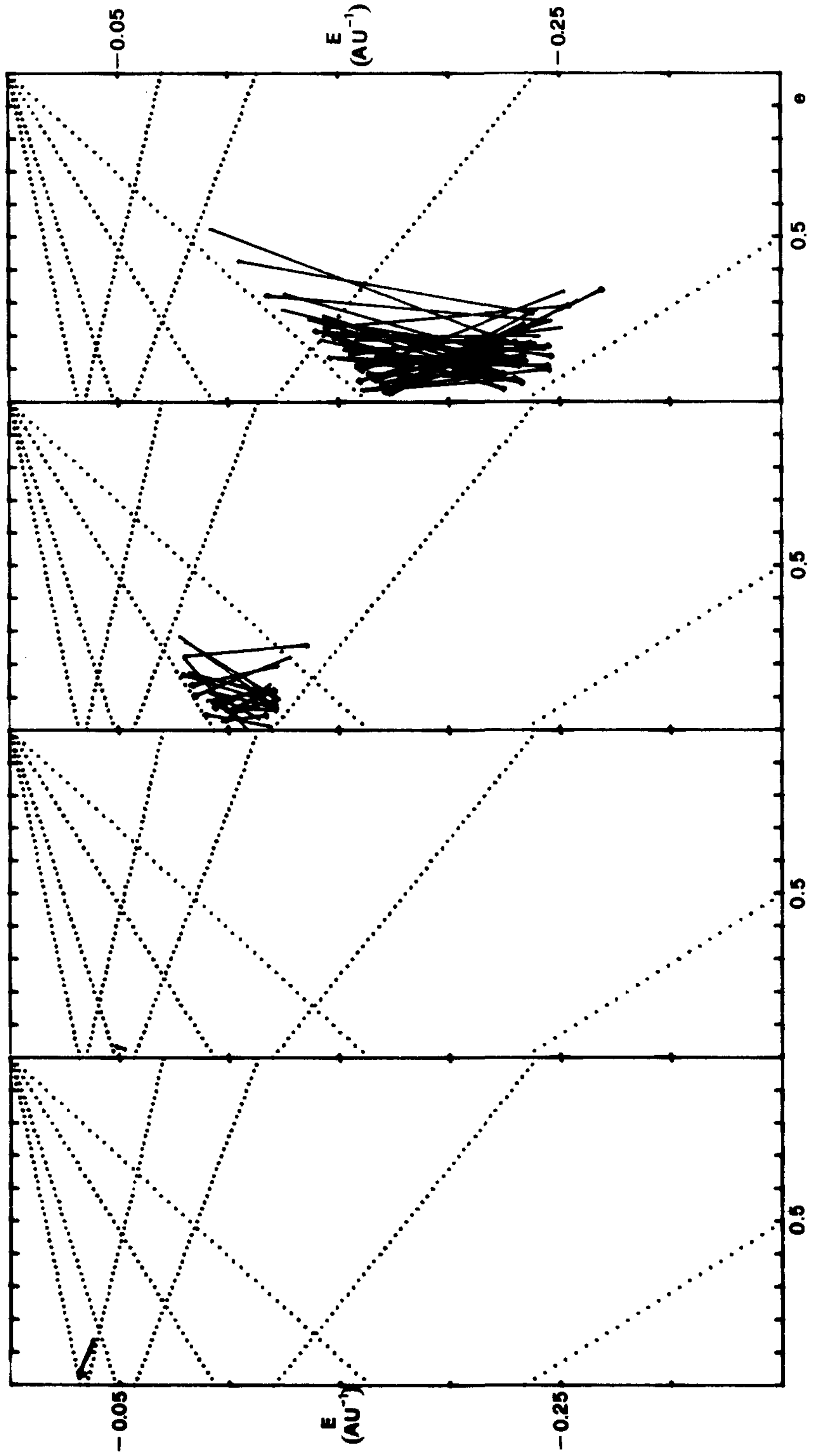

Fig. 7 - Same as Fig. 6 for objects of the four samples making "non-intersecting transitions (see text).

ter. Let us call them non-intersecting transitions. In only one case we have found an object whose pre-encounter and post-encounter orbits do not cross and the semimajor axes of both the orbits are less than that of the planet (Saturn, in this particular instance); this seems a limiting case, where the interaction has taken place with Saturn close to its perihelion - its distance from the Sun at the time of closest approach being 9.10 AU - and the initial and the final orbits of the minor body where nearly circular (e=0.06 for both).

Fig. 7 shows the cases of these "non-intersecting transitions" found in the four samples. Also in this figure the number of objects increases substantially passing from Neptune to Jupiter: the numbers (4 for NEP, 1 for URA, 19 for SAT and 43 for JUP) are comparable, except that of Uranus, to those of the temporary satellite captures found in the same samples. There are also other connections with the satellite captures:

a) the ranges of orbital parameters in which the two processes are found are very similar, as is shown by a comparison of Table III with Table I;

b) in the samples JUP and SAT, 22 out of 43 and respectively 8 out of 19 of the objects making a non-intersecting transition undergo also a temporary satellite capture; these captures are equally divided between the two types described above. For Uranus and Neptune, we have to remark that the size of the samples is not large enough to allow the finding of a sufficient number of events, thus rendering any conclusion only tentative.

The preceding considerations have some implications for the orbital evolution of small bodies in the outer Solar System. All the four outer major planets are able to transform effectively cometary orbits as a consequence of close encounters. All of them can change a cometary orbit in such a way that the pre-encounter and the post-encounter ellipses do not cross. However, Uranus and Neptune can do so only for initial orbits of the minor body very similar to that of the planet, a case which may be very rare in the orbital evolution of a comet. On the other hand, both Jupiter and Saturn display a great efficiency in such processes; we know of several comets that have undergone these orbital transformations: the first six entries of Table VI of Carusi et al. (1982) are known examples of this type, the sixth one, the 1886 encounter of P/Brooks 2 with Jupiter being an extreme case. The ranges of orbital parameters of Table III agree well with the parameters of the comets cited above. Moreover, as in the case of the fictitious objects, some of the six comets underwent a temporary satellite capture during the encounter; these are the two well known cases of P/Oterma and P/Gehrels 3. As regards Saturn, due to the limits on the orbital parameters given in Table III, the same considerations done in the case of the temporary satellite captures are applicable: some orbits of comets in the "trans-jovian belt" (Kresák, 1972) are suitable for the non-intersecting transitions caused by encounters with Saturn, although no example of this type has been found yet in numerical integrations of the past evolutions of short-period comets or in the numerical integrations of Chiron's orbit. In this last case, we can notice that the orbit is too eccentric, and the Tisserand invariant with respect to Saturn too low (see Oikawa and Everhart, 1979) in order to have very low velocity encounters with that planet.

A final remark concerns the planetocentric trajectories of the non-intersecting transitions. Direct inspection of these patterns has shown that most of them are of the very simple type reported in Figs. 1 and 3; this pattern has been encountered very frequently also by Carusi et al. (1982) in their study of orbital patterns at close encounters of minor bodies with Jupiter.

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