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On the existence of a comet belt beyond Neptune

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Summary. The possible existence of a comet belt in connection with the origin of the short-period comets is analysed. It is noted that the current theory – that these comets originate as near-parabolic comets captured by Jupiter and the other giant planets – implies an excessive wastage of comets lost in hyperbolic orbits, which is avoided in the present model.

The following picture is predicted. Solid conglomerates up to $\sim 10^{18}$ g were formed by gravitational instabilities in the belt region (about 35–50 AU). A further fragmentation–accretion process led to a power-law mass distribution similar to that observed in the asteroids. Since then, close encounters between members of the belt have provoked the diffusion of some of them with the effect that they have become subject to the strong perturbations of Nepture. Of these a small number pass from one planet to the next inside and end as short-period comets.

By means of a Monte Carlo method, the influence of close encounters between belt comets is then studied in relation to the diffusion of their orbits. It is concluded that if such a belt contains members with masses equal to or greater than that of Ceres, the orbital diffusion could proceed fast enough to maintain the number of observed short-period comets in a steady state.

1 Introduction

A comet belt located beyond Neptune has been suggested as a possible source of the observed comets. In an early version, Kuiper (1951) pointed out that such a belt would be the remnant of the outermost parts of the solar nebula, between about 35–50 AU, left behind after the formation of planets. More recently, Kuiper (1974) made reference again to this belt, specifying that comet-like masses of about $10^{17}–10^{18}$ g, perhaps 10^{11} in number, would have been formed there.

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16

With the purpose of verifying the presence of such a belt observationally, Hamid, Marsden & Whipple (1968) tried to measure possible perturbations in the motions of some periodic comets of more than one apparition and aphelia greater than 35 AU. Since they found no such perturbations, they concluded that the assumed belt, if it exists, could not have a mass greater than $0.5\,M_\oplus$ (Earth masses) if it is placed at 40 AU from the Sun or $1.3\,M_\oplus$ if at 50 AU.

Whipple (1972) has also made reference to the existence of a comet belt, suggesting that it could be responsible for the perturbation in the latitude of Neptune which had been previously attributed to Pluto.

In this paper I intend to analyse the existence of such a comet belt in connection with the origin of the short-period comets.

2 Apparent overabundance of short-period comets

There are 73 observed short-period comets (SP comets) with periods $3.3 < P < 13$ yr (Everhart 1972). The mean life of the SP comets is about 1400 yr, corresponding to an average of 200 revolutions with $\bar{P} = 7$ yr (Delsemme 1973). To maintain this population in a steady state it is necessary to incorporate $73/1400 \simeq 0.05$ comets yr^{-1}.

The hypothesis has been stated that the SP comets come from long-period comets captured by Jupiter and the other giant planets through successive moderate perturbations (see, e.g. Havnes 1970; Vaghi 1973). Everhart (1972) has shown through a numerical study that the orbital characteristics of the SP comet family can be explained, at least qualitatively, if it is assumed that these come from near-parabolic comets (NP comets) with small inclinations and perihelia in the range $4 < q < 6$ AU. However, from Everhart's study and assuming a steady state, Joss (1973) found that the rate of captures would be 40 000 times less than observed. From the observed flux of long-period comets, Kresák & Pittich (1978) also concluded that the rate of captures of long-period comets by Jupiter is insufficient to explain the observed number of SP comets. They estimated a rate of one comet captured in a few centuries, so the discrepancy in this case would be about an order of magnitude. Delsemme (1973) succeeded in obtaining a good agreement between the theoretical and observed values, assuming for this purpose the presence of about 30 000 to 100 000 intermediate-period comets.

The number of SP comets, then, appears to be controversial. This problem can be analysed, however, from another point of view. Numerical studies show that most NP comets entering the planetary region are lost in hyperbolic orbits after successive passages (Everhart 1976). If the SP comets come from the NP comets though, we may ask 'how many comets are lost in hyperbolic orbits for each one incorporated into the SP comet family?' Everhart (1977), using a Monte Carlo method, has calculated the probabilities that NP comets entering the zones of influence of the giant planets are finally transferred to SP comet-like orbits controlled by Jupiter. He assumed for the NP comet orbits an average inclination of 6°. He found that the probabilities were: Jupiter $p_J \simeq 1/128$, Saturn $p_S \simeq 1/700$, Uranus $p_U \simeq 1/3200$ and Neptune $p_N \simeq 1/6000$. Those comets not incorporated into the SP comet family are finally ejected along hyperbolic orbits. According to Everhart, Jupiter controls the comets with perihelia $q \lesssim 5.8$ AU ($\Delta q_j = 5.8$ AU), Saturn those with perihelia $5.8 \lesssim q \lesssim 10.7$ AU ($\Delta q_S = 4.9$ AU), Uranus $10.7 \lesssim q \lesssim 22$ AU ($\Delta q_U = 11.3$ AU) and Neptune $22 \lesssim q \lesssim 34$ AU ($\Delta q_N = 12$ AU).

Let us apply Everhart's results. Let N be the number of NP comets with orbits of small inclinations ($0° < i < 9°$, $\bar{i} = 6°$), coming into the planetary region ($q < 34$ AU) per unit time. The number of N_{SP} finally incorporated into the SP comet family will be

$$N_{SP} = N(p_J f_J + p_S f_S + p_U f_U + p_N f_N),$$

where f_i is the fraction of comets falling within the control zone of planet i. For the comets entering the planetary region from the Oort cloud, all perihelia are equally probable because of stellar perturbations (Öpik 1966; Weissman 1977). Hence, we have $f_i = \Delta q_i/\Delta q_T$ where $\Delta q_T = 34$ AU. Substituting the respective values, one obtains

$$N_{SP} = N(1/128 \times 0.17 + 1/700 \times 0.15 + 1/3200 \times 0.33 + 1/6000 \times 0.35)$$
$$= N \times 1/600.$$

This implies that for each SP comet, 600 NP comets with $i \lessdot 9°$ are finally ejected in hyperbolic orbits, that is

$0.05 \times 600 = 30$ NP comet yr^{-1}.

Taking into account that the orientations of the orbital planes of NP comets are random, the group with $i < 9°$ would represent only 0.006 of the total. The capture probability decreases quickly as i increases. Then, for an estimation of the number of ejected comets for each new SP comet, we can multiply by a factor of 10 the value previously calculated. Accordingly about 300 NP comets would be lost per year. For the whole life of the solar system (4.5×10^9 yr), this gives a total number of ejected comets of $300 \times 4.5 \times 10^9 = 1.35 \times 10^{12}$. This amount is an order of magnitude greater than the number of members proposed by Oort (1950) for the comet cloud, which seems to be excessive.

In view of this difficulty, it seems appropriate to raise the question whether the source of the SP comets is located close to the planetary region. In this way the objection of the excessive wastage of matter would be avoided.

3 Formation of cometesimals in the early solar nebula beyond Neptune

An approximate idea of the distribution of material in the early solar nebula could be obtained by supposing that the solid matter contained in it, is at present located in the planets. By dispersing the solid matter of the planets in an equatorial disc, the values of surface density shown in Table 1 are obtained. Presumably, the real values are greater than these because of the ejection of solid matter by planetary perturbations once the planets were formed (Fernández 1978). The ratios of rocky and icy material to the gaseous components of H and He in the giant planets have been taken from the models of Podolak & Cameron (1974) and Stevenson (1978).

The values of surface density in the solar nebula fit well enough the following relation

$$\sigma = \sigma_0/r^2 \qquad (1)$$

where $\sigma_0 \simeq 4M_\oplus$ and r is the distance to the Sun. The values obtained by means of equation (1) are shown in the third column of Table 1.

Table 1. Surface density in the early solar nebula (in $M_\oplus$. AU^{-2}).

r (AU)	σ (deduced from the planetary masses)	σ_0/r^2
5.2	0.140	0.150
9.5	0.042	0.044
19.2	0.010	0.011
30.0	0.005	0.004

It is reasonable to assume that equation (1) maintains its validity up to distances of 35–50 AU, where the existence of a comet belt has been proposed. In this case we can calculate the amount of solid mass contained in it at the beginning as

$$M_{\mathrm{belt}} = \int_{r_1}^{r_2} \sigma_0/r^2 \times 2\pi r\, dr = 2\pi\sigma_0 \log(r_2/r_1) \tag{2}$$

Setting $r_1 = 35$ AU and $r_2 = 50$ AU, we obtain $M_{\mathrm{belt}} \simeq 9M_{\oplus}$, which is much greater than the upper total mass admitted for the belt. The question arises whether this matter could condense and form solid conglomerates of cometary size ('cometesimals').

Goldreich & Ward (1973) visualize planetary formation through various stages. In the first stage, condensed dust particles would settle into a thin disc, then the gravitational collapse of the particles would form a 'first generation of planetesimals'. They showed that in this stage the disc would remain gravitationally unstable, leading to a grouping of the first-generation planetesimals into clusters, which by collapse would form into a 'second generation' of planetesimals.

In the conditions postulated here for the solar nebula, the upper size of such Goldreich–Ward clusters is imposed by the solar tide. Hence, the largest mass of a conglomerate will be $m \simeq \sigma R_{\mathrm{T}}^2$, where R_{T} is the tidal radius given by $R_{\mathrm{T}} \simeq r(m/M_{\odot})^{1/3}$, $M_{\odot}$ being the solar mass. Therefore we have

$$m \simeq \sigma r^2 (m/M_{\odot})^{2/3} = \sigma_0^3/M_{\odot}^2 = 3 \times 10^{18}\,\mathrm{g}. \tag{3}$$

The above result is of the same order as the masses ascribed to the largest comets.

It is noted that equation (3) does not depend on the Sun distance r, implying that the largest cometesimal masses would be similar in the hypothetical belt and in the region of the giant planets.

The result of equation (3) is only an initial value because such cometesimals most probably were subject to an accretion–fragmentation process, leading to the formation of greater planetesimals, as has been described by Hartmann (1978) and Greenberg *et al.* (1978). Such a process may also have occurred in the belt region, but the lower density of material there impeded the formation of a massive planet, which would be detected by its gravitational perturbations on Neptune. We cannot, however, reject the possibility of formation of bodies of asteroidal or lunar size, conforming for the comet belt a mass distribution similar to that of the asteroids.

Biermann & Michel (1978) have also studied the formation of comets by the Goldreich–Ward mechanism. However, they consider the formation of comets of the Oort cloud *in situ*, that is at about 10^4 AU from the Sun. The extension of this mechanism to such huge distances is doubtful and the authors have to presuppose the presence of a very massive solar nebula (2–$3M_{\odot}$). None-the-less, the comet belt is explained in a more direct way if we suppose that it is composed of the extenal residuals to Neptune's orbit which were not incorporated in the planet itself.

4 Dynamical evolution of the comet belt: The model

Assuming rather circular orbits for the belt comets, the relevant question is 'how they can evolve so as to attain orbits like those corresponding to SP comets?' Kuiper (1951) established that Pluto would be responsible for the dispersal of comets from the belt until they were subject to the much stronger perturbing influence of Neptune. However, there are two arguments against the possibility that Pluto can play an important role. First, its mass seems to be much less than previously believed, perhaps only some $10^{-3} M_{\oplus}$ (Cruikshank *et al.*

1976). Second, given the orbital characteristics of Pluto, it seems unlikely that it passes through regions of the belt, supposing this lies near the ecliptic plane. In effect, its inclination is rather large (17°), and its argument of perihelion is about 90° (Williams & Benson 1971), so that it is far away from the ecliptic plane when it is near the aphelion.

It remains then to consider the gravitational interactions between the belt comets as a possible cause of evolution. If some of these comets contain a rather large mass, close encounters can play an important role in the dispersal of members of the belt.

With the scope of analysing how the mass distribution influences the dispersal of comets in the belt, a large number of close encounters were simulated by means of a Monte Carlo method. The perihelia and aphelia of the interacting comets were taken at random within certain Sun distances r_1 and r_2 imposed on the belt. Each pair of orbits yielded a close encounter which happened in one of the intersection points. A small angle, taken at random between 0 and 10°, was assigned to the orbital planes of each pair. For the mass distribution, a power law like the one that holds for the asteroids was adopted. Hence, the number $n(m)dm$ of comets in the range $(m, m + dm)$ will be given by

$$n(m)\,dm = Am^{-\alpha}\,dm, \tag{4}$$

where A is a constant and $1.5 < \alpha < 2$ (Harris 1978).

For the simulation, I have taken into account the dependence between the number of close encounters per unit time n_c and the masses m_i and m_j of the interacting comets. For this, the following relation is fulfilled

$$n_c(m_i, m_j)\,dm_i\,dm_j = U/V \times n(m_i)n(m_j)S_E(m_i, m_j)\,dm_i\,dm_j, \tag{5}$$

U being the encounter velocity and V the volume of the belt, which has been approximated by a torus centred at the Sun with radii r_1 and r_2. Hence $V = \pi^2/4\,(r_2 - r_1)^2(r_2 + r_1)$.

$S_E(m_i, m_j) = \pi R_E^2$ is the cross-section of close encounters between the masses m_i and m_j. For the model, I have adopted $R_E = KR_c$, K being a proportionality factor and R_c the radius of collisions, enlarged by gravity, given by

$$R_c = \eta(m_i^{1/3} + m_j^{1/3})\left(1 + \frac{2G}{U^2\eta^2}\frac{m_i + m_j}{m_i^{1/3} + m_j^{1/3}}\right)^{1/2} \tag{6}$$

where $\eta = (4/3\,\pi\rho)^{-1/3}$ and ρ is the density of the cometary nuclei for which I have adopted $1\ \mathrm{g\,cm^{-3}}$.

The total number of close encounters per unit time will be given by

$$n_{tot} = \frac{U}{V}\int_{M_{min}}^{M_{max}} n(m_i)\,dm_i \int_{M_{min}}^{m_i} n(m_j)S_E(m_i, m_j)\,dm_j \tag{7}$$

M_{max}, M_{min} being the maximum and minimum masses within the mass distribution in the belt.

Finally, the probability $p_c(m_i, m_j)dm_idm_j$ that the comets participating in a close encounter have masses in the ranges $(m_i, m_i + dm_i)$ and $(m_j, m_j + dm_j)$ will be given by

$$p_c(m_i, m_j)\,dm_i\,dm_j = \frac{n_c(m_i, m_j)}{n_{tot}}\,dm_i\,dm_j. \tag{8}$$

Then, given a pair of orbits, the encounter velocity $\mathbf{U} = \mathbf{V}_j - \mathbf{V}_i$ was calculated, where $\mathbf{V}_j$, $\mathbf{V}_i$ are the orbital velocities at the encounter point. Next, the comets were assigned random masses m_i and m_j, fulfilling the probability distribution given by equation (8).

Let $\mathbf{V}_G$ be the centre-of-mass velocity of m_i and m_j in a heliocentric frame of reference. The orbital velocities before the encounter will be given by: $\mathbf{V}_G + \mathbf{u}_i$ and $\mathbf{V}_G + \mathbf{u}_j$, where $\mathbf{u}_i$ and $\mathbf{u}_j$ are the velocities relative to the centre of mass. Due to the close encounter, the vectors $\mathbf{u}_i$ and $\mathbf{u}_j$ do not modify their magnitudes but they are deflected through an angle γ given by (Woolfson 1978)

$$\tan\frac{\gamma}{2} = \frac{G(m_i + m_j)}{DU^2} \tag{9}$$

where D, the 'encounter parameter', is the minimum distance of a comet with respect to the unperturbed trajectory of the other one. D was taken at random for each encounter, but such that $D < R_E$ and agreeing with the probability distribution function $p(D)dD = DdD/R_E^2$. When $D < R_c$ a collision occurred and the result was rejected from the computations.

The heliocentric velocities after the encounter were calculated as $\mathbf{V}_i' = \mathbf{V}_G + \mathbf{u}_i'$ and $\mathbf{V}_j' = \mathbf{V}_G + \mathbf{u}_j'$, where $\mathbf{u}_i'$ and $\mathbf{u}_j'$ are the deflected relative velocities. The new orbital elements were then computed from $\mathbf{V}_i'$ and $\mathbf{V}_j'$.

The radii $r_1 = 35$ AU and $r_2 = 50$ AU were adopted as lower and upper limits of the belt. Also, a total mass of $1\,M_\oplus$ was assigned to it. $M_{\min} = 10^{15}$ g was taken as the minimum mass in the mass distribution, corresponding approximately to the faintest comets. A set of values between $10^{21} - 10^{26}$ g were considered for the maximum mass. For the exponent α of the mass distribution a set of values between 1.5 and 1.9 was used. For the proportionality factor K of the close encounter cross-section I used two values: 20 and 50.

5 Results

The histograms of Fig. 1 show the number of comet orbits whose perihelia of aphelia lie outside the belt limits due to close encounters. The number of close encounters considered in each sample corresponds to a period of 400 yr. To cover this period it was necessary to calculate sets of tens to hundreds of thousands of close encounters. The derivation of the number of close encounters occurring in a given period was made from equation (7), taking for U the average value resulting from the computation of a set of close encounters. With the constraints imposed on comet orbits $\bar{U}$ is about 5×10^4 cm s^{-1}.

As can be seen, the orbital diffusion for $M_{\max} = 10^{26}$ g is remarkable. The number of comet orbits whose perihelia cross the lower limit of 35 AU is 713, giving a rate of inward diffusion of ~ 1.8 comet yr^{-1}. The smaller $M_{\max}$, the smaller the rate of diffusion of the orbital perihelia giving values of 0.8, 0.6 and 0.2 comet yr^{-1} for $M_{\max} = 10^{25}$, 10^{24} and 10^{23} g. Somewhat greater ratio of diffusion were obtained for the aphelia.

We can assume that between the Neptune orbit and the lower limit of the comet belt, that is 30–35 AU, there is a transition region in a steady state. That is, for each incorporated comet coming from the belt, another is removed from the transition region because of the strong perturbations of Nepture. In accordance with this, the number of comets coming from the belt that are transferred into Neptune's gravitational control would be of the same order as the diffusion rates previously calculated.

All the results given above correspond to the factor $K = 50$. By adopting $K = 20$ we obtained similar results from a qualitative point of view. Quantitatively, the results obtained were smaller by a factor of about 4, which is reasonable because many somewhat more distant encounters were left out of the computations. For the same reason, we must expect the values represented in Fig. 1 to be somewhat smaller than those occurring in a real situation.

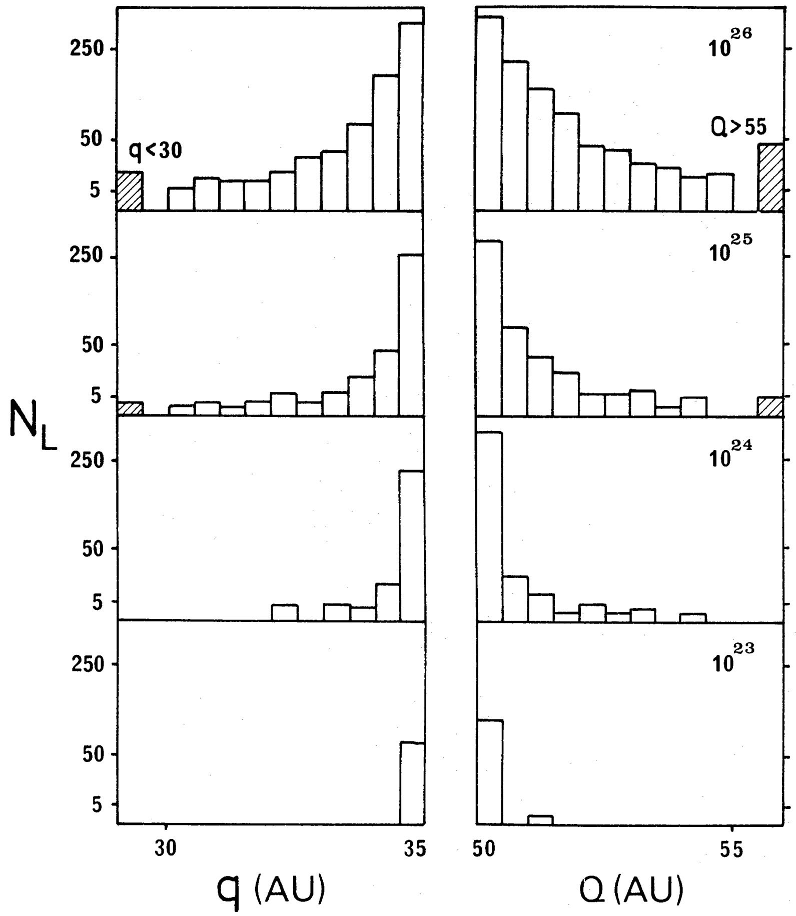

Figure 1. Histograms showing the number of comets N_L whose perihelia or aphelia lie outside the limits assigned to the belt (35–50 AU) because of close encounters. The comets have been grouped into intervals of 0.5 AU. The time period considered is 400 yr. The four cases correspond to values of maximum masses M_{max} (g) appearing at the upper right of each picture. The other parameters have values $K = 50$ and $\alpha = 1.75$.

The changes in perihelia and aphelia after close encounters $\Delta q_i = q_i$ (final) $- q_i$ (initial) and $\Delta Q_i = Q_i$ (final) $- Q_i$ (initial) were computed for comets with $m < 10^{20}$ g, that is, those with smaller masses but experiencing larger orbital variations. Hence, the mean changes $\overline{\Delta q}$, $\overline{\Delta Q}$ and standard deviations $\sigma_{\Delta q}$, $\sigma_{\Delta Q}$ were obtained for each one of the comet samples corresponding to a different value of M_{max}. Next, the mean change and standard deviation in the perihelion and aphelion of a comet with $m < 10^{20}$ g, during the whole life of the solar system T, were estimated from $\overline{\Delta q_T} = N_T \cdot \overline{\Delta q}$, $\sigma^2_{\Delta q_T} = N_T \cdot \sigma^2_{\Delta q}$ (with similar expressions for the aphelion). In the above expressions, N_T is the mean number of close encounters experienced by a belt comet of mass m through all the life of the solar system and is given by

$$N_T(m) = \frac{UT}{V} \int_{M_{min}}^{M_{max}} n(M) S_E(M, m)\, dM. \tag{10}$$

Since the number of close encounters depends on m, an average of N_T in the range $10^{15} < m < 10^{20}$ g was considered.

The values obtained for the mean changes and standard deviations are shown in Fig. 2 as a function of the maximum mass M_{max}. The same parameters as in Fig. 1 were used.

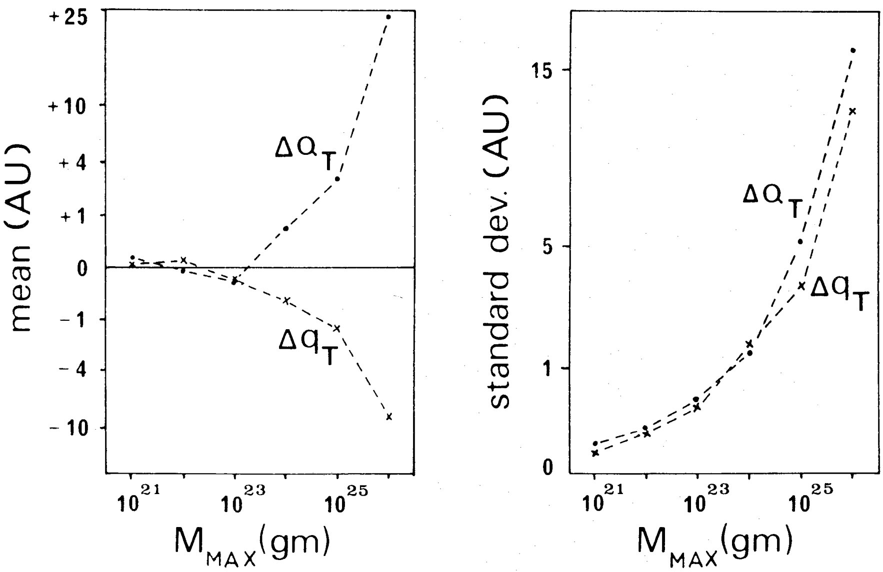

Figure 2. Mean and standard deviation of the perihelion and aphelion changes Δq_{T} and ΔQ_{T} of a belt comet, due to close encounters through all the solar system life, as a function of the maximum mass $M_{\max}$.

For $M_{\max} = 10^{26}$ g, large values of $\overline{\Delta q}_{\mathrm{T}}$, $\sigma_{\Delta q_{\mathrm{T}}}$, $\overline{\Delta Q}_{\mathrm{T}}$ and $\sigma_{\Delta Q_{\mathrm{T}}}$ were obtained, implying a large orbital dispersion in accordance with the results shown in Fig. 1. Obviously the latter results are a rough estimate because such dispersion would introduce profound modifications in the orbital properties of the belt comets and these would have to be taken into account in a more detailed study. For $M_{\max} = 10^{25}$ g, the orbital diffusion is still remarkable. Thus, by assuming a Gaussian distribution for Δq_{T}, the number of comets reaching a $\Delta q_{\mathrm{T}} \leq -5$ AU after $T = 4.5 \times 10^9$ yr is about 0.13 times the total. For smaller upper masses this fraction decreases very fast to 2.5×10^{-3} and 2.5×10^{-6} for $M_{\max} = 10^{24}$ and 10^{23} g.

The mean number of cometary orbits N_q acquiring perihelia $q < 35$ AU per year is shown in Fig. 3 as a function of the exponent α of the mass distribution. The values 10^{24}, 10^{25} and 10^{26} g were taken for $M_{\max}$. In all cases one can verify that N_q is strongly dependent on α. For smaller values of α, almost all of the mass is concentrated in the largest members of the distribution; thus, there are fewer small comets and N_q is also smaller. The larger the value of α, the greater the number of of small masses, whereby N_q also increases.

In the examples analysed in Figs 1 and 2, we adopted an average value of $\alpha = 1.75$. Nevertheless it is probable that in a population with the characteristics assigned to the belt, perhaps with the exception of only the largest members, the remaining ones would be subject exclusively to a fragmentation process by collisions. In this case, α could be greater than the value adopted previously, perhaps about 11/6 (Dohnanyi 1969). Hence, the above calculated rates of orbital diffusion would also increase.

Some numerical experiments have also been made to modify the range of inclinations for the orbital planes of interacting comets between 0 and 30°. Greater inclinations imply greater encounter velocities U. In all cases the results obtained were similar, and this can be explained by a sort of compensation since the increase in U and, therefore, in the number of close encounters per unit time, tends to favour greater perturbations. On the other hand, as U increases the deflection angle γ diminishes having an opposite effect.

To summarize: in a belt with the characteristics described above, we can expect an inward diffusion rate of some comets per year if it contains upper masses comparable with that of the Moon, or several tenths if it contains upper masses comparable with that of Ceres.

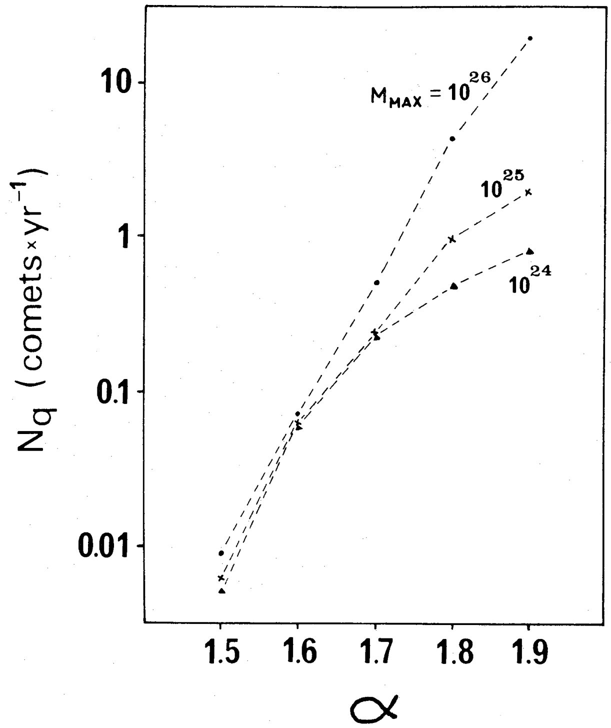

Figure 3. Mean number of comets per year N_q whose orbits attain perihelia $q < 35$ AU as a function of the exponent α of the mass distribution.

6 Later evolution of the comets leaving the belt

Once the comets have reached the neighbourhood of Neptune, their evolution proceeds at a faster rate in the manner described by Everhart (1977) for the comets captured from the NP comet influx. According to the author's results, the transfer efficiencies from one orbit to the next inside are: Uranus–Saturn 40/69, Saturn–Jupiter 229/500 and Jupiter–SP comet 92/229. As can be seen, the transfer efficiencies do not differ so much from one case to another and have values rather close to 1/2. The comets that are not transferred to an inner orbit are ejected along a hyperbolic one. We can add, as a reasonable assumption, that the transfer efficiency Neptune–Uranus is also about 1/2. By combining the above results, we arrive at the probability of a comet reaching the orbit of Neptune and finally becoming a SP comet is $(1/2)^4 = 1/16$. If the rate of new SP comets is 0.05 per year, $0.05 \times 16 = 0.8$ comets per year coming from the belt are required, on the hypothesis that this is the only source for this group of comets. As we saw in the last section, this is within the possibilities of orbital diffusion of belt comets by close encounters, assuming that it contains upper masses like that of Ceres or somewhat greater.

The latter results imply a greater economy of matter to maintain the observed number of SP comets. Compared with the 300 comets per year required in the theory of capture from a NP comet influx, only 0.8 are required here to maintain the SP comet family in a steady state.

Furthermore, we see that half the comets coming into the planetary region, that is 0.4 comets per year, are subject to strong perturbations by Uranus and Neptune until they are ejected or placed into the Oort cloud. Previously, it was pointed out that Neptune (Kuiper 1951; Safronov 1972) and Uranus and Neptune (Fernández 1978) were the principal contributors of matter to the Oort cloud. The Oort cloud would then be receiving new members from the comet belt, sent there by the perturbations of Uranus and Neptune. In a forthcoming paper the author proposes to analyse the later evolution of cometary orbits, leaving the Uranus–Neptune region along near-parabolic orbits, taking into account the perturbations of nearby stars.

7 Conclusion

The properties of a hypothetical comet belt located beyond Neptune and its suitability as a source of the SP comets were discussed. The following picture of the formation and evolution of such a belt was devised. The region of the solar nebula between 35 and 50 AU could have initially contained a minimum solid mass of about $10 M_{\oplus}$. There, solid conglomerates or cometesimals with masses up to about 10^{18} g would have formed by gravitational instabilities. The subsequent evolution of such cometesimals through an accretion–fragmentation process would have determined a power-law mass distribution.

It was seen that with maximum masses in the order of Ceres or somewhat greater within the mass distribution in the belt, the orbital diffusion proceeds fast enough to supply the necessary amount of SP comets. The comets would cross over the planetary region from the belt to the zone interior to Jupiter through perturbations by the giant planets.

If bodies with masses of some 10^{24} g are really found in the belt: could they be observed? At distances to the Sun of 40–50 AU and assuming for them a geometric albedo of ~ 0.5 such as that suspected for Pluto (Cruikshank, Pilcher & Morrison 1976), such bodies would be of apparent magnitude $17 - 18$. Thus, they could be discovered, although their extreme faintness would make this task very difficult and it would explain why they have escaped detection until now. We have until recently lacked knowledge of any small bodies orbiting the Sun in the outermost part of the planetary region. Kowal (1977) has, however, discovered an object of magnitude 18 moving in a low-inclination orbit with perihelion and aphelion close to the orbits of Saturn and Uranus respectively. Perhaps we are faced here with one of the brightest comets coming from the belt and diffusing inwards through planetary perturbations. The discovery of new bodies far beyond Jupiter would undoubtedly shed light on this question as well as on the existence of the hypothesized comet belt.

Going further in our speculations, it is possible to suppose that the belt has been experiencing a strong depletion from the beginning until now. This presumably happened with the population of the astroidal belt (Chapman & Davis 1975). Then, we can expect that in early epochs the influx of SP comets must have been greater than it is at present.

The hypothesis of a comet belt beyond Neptune has not been presented as a substitute for the Oort cloud but as complementary. As well as the belt being the source of the observed SP comets, the Oort cloud is principally the source of the long-period comets. This cloud was formed with the residual solid matter mostly contained in the Uranus and Neptune region. But once it was depleted, the cloud has continued to receive material from the belt. In this way a common origin is attributed to both sources, and therefore to the comets.

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