COMET SHOWERS

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Abstract. Variations in the influx rate of incoming Oort cloud comets, leading to the occurrence of comet showers, are reviewed with special emphasis on the dynamical processes that produce them. It is found that comet showers as intense as 10–100 times the background comet flux may occur at average intervals of several 10^7years, being very close stellar passages at distances $\approx 10^4 AU$ and, perhaps, penetrating encounters with intermediate-size molecular clouds the trigger mechanisms. Penetrating encounters with giant molecular clouds and stellar passages at distances of a few $10^3 AU$ may trigger comet showers about $10^2 - -10^3$ times more intense than the background comet flux at average intervals of a few 10^8years. The impact cratering record on the Earth does not show any clear evidence of past comet showers. Some orbital properties of new and dynamically young comets suggest that the influx rate of Oort cloud comets is currently near its background level.

1. Introduction

Most discovered comets have orbital periods $P > 200$ yr. These are known as long-period (LP) comets. About 15% of them are found to have periods $P > 10^6 yr$, that correspond to original semimajor axes $a_{\mathrm{orig}} > 10^4 AU$ (i.e. their values of a before being perturbed by the planets). These comets may be coming from the Oort cloud for the first time and for this reason Oort (1950) called them "new" comets.

The discovery rate of Earth-crossing LP comets has remained nearly constant since the middle of the last century. By making allowance of missed comets, the rate of passages of LP comets brighter than absolute magnitude $H_{10} \approx 10.5$ is estimated to be about $3 yr^{-1}$. By assuming that about 15% of them are new, we obtain a passage rate of Earth-crossing new comets of about one every two years (Fernández and Ip 1991).

Nongravitational forces may introduce some uncertainty in the derived values of a_{orig}. To avoid this problem as much as possible, we can limit ourselves to the sample of new comets with larger perihelion distances for which nongravitational forces presumably have a lesser effect (e.g. Marsden and Sekanina 1973). The distribution of $(1/a)_{\mathrm{orig}}$ of new comets with perihelion distances $q > 2AU$ shows a concentration in the range $2 \times 10^{-5} < (1/a)_{\mathrm{orig}} < 5 \times 10^{-5} AU^{-1}$(Fig.1), i.e. semimajor axes in the range $2 - 5 \times 10^4$AU. Any theory about the space distribution of comets in the Oort cloud and the forces responsible for bringing some of its members to the inner planetary region must take this property into account.

A relevant question for the understanding of the origin and evolution of the solar system is whether the influx rate of Oort cloud comets varies with time. By assuming that comets formed in the Uranus-Neptune region from where they were scattered by planetary perturbations (Kuiper 1951; Safronov 1972; Fernández 1978), Wetherill (1975) concluded that a late heavy bombardment of the terrestrial planets with cometary bodies took place about 500 Myr after the solar system formation. The influx rate of comets steadily decreased by two-three orders of magnitude from that epoch to the present (Fernández and Ip 1983). The study of the cratering

S. Ferraz-Mello (ed.), Chaos, Resonance and Collective Dynamical Phenomena in the Solar System, 239–254.

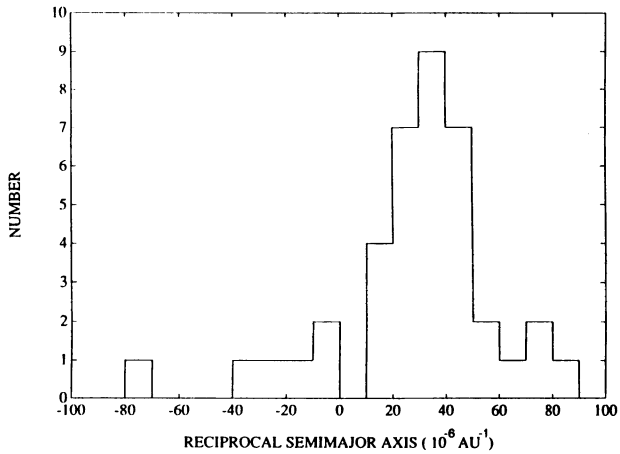

Fig. 1. Distribution of original reciprocal semimajor axes of new comets with perihelion distances $q > 2AU$ taken from Marsden's (1989) catalogue.

record of the Earth, Moon and the other terrestrial planets may shed light on the population size of stray bodies in the past.

The time variation in the influx rate of comets might have been due not only to the depletion of some reservoirs, but also to random strong perturbations of the Oort cloud. If we imagine the solar system surrounded by a cloud of comets –the Oort cloud– a passing star penetrating deeply into it might have large dynamical effects, among them a dramatic increase in the fraction of comets deflected to the planetary region. A sudden enhancement in the influx rate of new comets – of short duration on cosmogonic time scales – will follow, which Hills (1981) has called a "comet shower".

Comet showers might have had a considerable influence on the evolution of the atmospheres of the Earth and the other terrestrial planets (e.g. Chyba 1987) and the occurrence of mass extinctions like the one in which the dinosaurs and nearly three-quarters of all the species alive at the end of the Cretaceous disappeared (e.g. Raup and Sepkoski 1984). Several authors have claimed that an evidence of past comet showers is found in the impact cratering record on the Earth (e.g. Alvarez and Muller 1984). This topic will be addressed below.

2. The Perturbation of comets in the Oort cloud: basic concepts

Oort cloud comets are subject to the action of external perturbers which can be identified with passing stars, molecular clouds and galactic tides. As a result, comets have been thermalized over the solar system age, at least those contained in the outer portions of the Oort cloud, say at heliocentric distances $r \gtrsim 10^4 AU$ (e.g. Duncan et al. 1987). But not all the directions of the velocity vectors of thermalized

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comets will be possible, for Oort cloud comets entering the inner planetary region, say with perihelia half-way between Jupiter and Saturn $q < q_L \approx 7.5 AU$, will be quickly removed by planetary perturbations, owing to the fact that their typical energy changes are greater than their binding energies in the Oort cloud (Fernández 1981). Since the velocity vectors of these comets fall very close to the solar direction, there will be an empty region in the velocity phase space known as loss cone (Hills 1981; Torbett 1986).

For a thermalized cometary population, the fraction of comets of semimajor axis a having perihelion distances $q < q_L$ will be approximately given by

$$F_L \cong 2q_L/a, \tag{1}$$

provided that $q_L << a$(Hills 1981). Thus the loss cone will have an angular radius of $2F_L^{1/2}$ radians and the solar direction as the axis.

Following Hills we will also introduce the concept of "smear cone" as a convenient device given by the fraction of loss cone that is filled with comets of a certain a after being perturbed. Let us consider Oort cloud comets at a time-average heliocentric distance $r = 1.5a$ and orbital velocity

$$v_c^2 = GM_\odot/3a, \tag{2}$$

where G is the gravitational constant and $M_\odot$ is the Sun's mass. Due to external perturbers (e.g. passing stars), a fraction of these comets will continuously diffuse into their loss cone. If Δv_T is the change in the transverse component of the cometary velocity due to an external perturber, the smear cone in the velocity phase space will be given by

$$F_S = \Delta v_T^2/4v_c^2. \tag{3}$$

When $F_S << F_L$, the loss cone will be almost empty and this occurs for small values of a. For larger a F_S will increase so that a larger proportion of their respective loss cones will be refilled until they get full when $F_S = F_L$. Therefore, for a certain a external perturbers will keep a fraction f of loss cone refilled at any time, which is given by

$$f = (F_S/F_L)_{T=P} = \frac{3a^2\Delta v_T^2}{8GM_\odot q_L} \tag{4}$$

where $T = P$ means that we consider the change Δv_T over the orbital period $P = a^{3/2}$years.

3. Perturbers acting continuously on Oort cloud comets

Passing – background – stars that do not penetrate the core of the Oort cloud and tides from the galactic disk exert a continuous perturbing action on Oort cloud comets. By contrast, very close stellar passages – that mainly affect comets along the star's path – or penetrating encounters with molecular clouds occur sporadically over time scales of the order of several 10^7 yr (Fernández and Ip 1991). The steady supply of new comets is thus due to the action of background stars and galactic tides. These perturbers will be analyzed in this section.

During an orbital revolution of period $P = a^{3/2}$ yr a comet will be perturbed by many stars. Let $s(D_\odot)dD_\odot = 2n_* D_\odot dD_\odot$ be the rate of stellar passages with impact parameters in the range $(D_\odot, D_\odot + dD_\odot)$. n_* is the stellar flux in the Sun's neighborhood of about 7 stars Myr^{-1} passing through a circle of 1pc-radius at an average encounter velocity with the Sun of $V = 30 kms^{-1}$. The cumulative change in the orbital velocity of the comet during P, Δv_*, will be expressed as (Fernández and Ip 1987)

$$\Delta v_*^2 = P \int_{D_m}^{D_L} \Delta v^2 s(D_\odot) dD_\odot, \tag{5}$$

where $\overrightarrow{\Delta v}$ is the impulsive change in $\mathbf{v}_c$ due to a single star passage which is given by

$$\overrightarrow{\Delta v} = \overrightarrow{\Delta v}_c - \overrightarrow{\Delta v}_\odot \tag{6}$$

where $\overrightarrow{\Delta v}_c$ and $\overrightarrow{\Delta v}_\odot$ are the impulses received by the comet and the Sun from the passing star. $D_m = (2n_* P)^{-1/2}$ is the minimum distance of closest approach to the Sun expected during P. D_M is the maximum distance of a passing star that may have some dynamical influence. It can be taken as infinity without too much error.

Let ψ be the angle between $\overrightarrow{\Delta v}_*$ and its transverse component; then we have

$$(\Delta v_*)_T^2 \cong \Delta v_*^2 < \cos^2 \psi >= 2/3 \Delta v_*^2. \tag{7}$$

Recent studies have shown that the galactic tidal force directed into the galactic disk has a dominant role in the dynamical evolution of Oort cloud comets as compared to stellar perturbations (e.g. Byl 1983; Heisler and Tremaine 1986; Morris and Muller 1986). The change in the transverse velocity of an Oort cloud comet of semimajor axis a at a galactic latitude ϕ due to the action of the tidal force of the galactic disk is

$$(\Delta v_{tide})_T = 3\pi G \rho a P \cos\alpha \sin 2\phi, \tag{8}$$

where α is the angle between the orbital plane and the plane perpendicular to the galactic disk containing the radius Sun-comet. ρ is the density of the galactic disk in the Sun's neighborhood. From the comparison of different gravitational potential models of the Galaxy with velocity dispersions of tracer stars, Bahcall (1984) derives a value of $\rho = 0.185 M_\odot pc^{-3}$. In the following we will adopt this value, although we should bear in mind that somewhat different results have been derived; for instance, Kuijken and Gilmore (1989) have found $\rho = 0.1 M_\odot pc^{-3}$. We note that the factor $\cos\alpha$ was overlooked in some previous works (Torbett 1986; Morris and Mueller 1986; Fernández and Ip 1991), thus implying that the galactic tidal effect was somewhat overestimated. We will assume that α can take any value between 0 and π and adopt an average value of $< \cos^2\alpha >= 1/2$.

Substituting Δv_T in eq.(4) by the expressions given by eqs.(5) and (8) we obtain the fractions of loss cone filled with comets, f_* and f_{tide}, as due to stellar perturbations and the vertical galactic tidal force, respectively. Eq.(8) shows that f_{tide}

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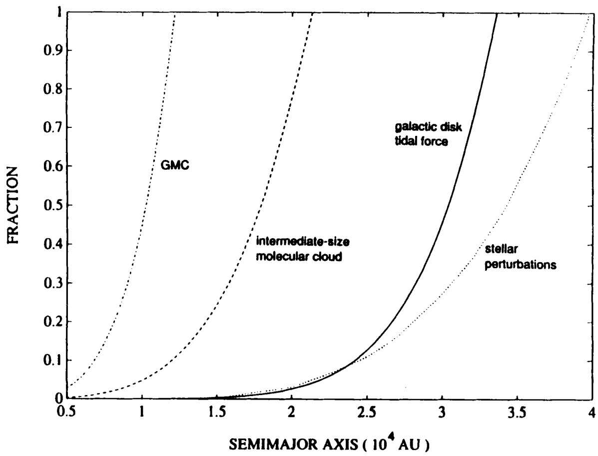

Fig. 2. Fraction of loss cone filled with comets as a function of the semimajor axis and for different perturbers.

depends on the galactic latitude ϕ. In the following we will neglect the galactic latitude dependence of $f_{\rm tide}$ and adopt an average value of $< \sin^2 2\phi >= 8/15$. We will return to the galactic dependence later on. As seen in Fig.2, the tidal force of the galactic disk fills the loss cones of Oort cloud comets with $a \gtrsim 3.3 \times 10^4$AU. This turns out to be somewhat smaller than the limiting semimajor axis of $a \approx 4 \times 10^4 AU$ for which the loss cone is filled by stellar perturbations. These results show the predominance of galactic tides in the dynamical evolution of Oort cloud comets. The combined effect of stellar perturbations and the vertical galactic tidal force determines a limiting semimajor axis $a = a_{fill}$ such that comets with $a > a_{fill}$ will have their loss cones permanently filled. We get

$$a_{fill} \simeq 3.16 \times 10^4 AU$$

This value turns out to be in good agreement with previous analytical derivations (Heisler and Tremaine 1986) and Monte Carlo simulations (Heisler 1990).

To compute the influx rate of Oort cloud comets in Earth-crossing orbits, i.e. able to contribute to the cratering of the surfaces of the Earth and the Moon, let us introduce the concept of "Earth cone" as the cone of angular radius $2F_e^{1/2}$ radians, where $F_e = 2q_e/a$ and $q_e = 1AU$, having the solar direction as the axis. Comets diffusing into their respective loss cones will be injected into the planetary region and a fraction of them F_e/F_L will become Earth-crossers.

Let us now assume a certain distribution of semimajor axes of Oort cloud comets of the kind

$$\Gamma(a)da \propto a^{-\alpha}da, \tag{9}$$

where the index α is unknown. Different values of α reflect different degrees of central condensation of the Oort cloud. We will discuss possible values in the range

$\alpha = 2-4$ as in some previous works (Bailey 1983; Fernández and Ip 1987). From numerical simulations that included planetary perturbations, stellar encounters and the galactic tide, Duncan et al. (1987) obtained a density profile of Oort cloud comets $\propto r^{-3.5}$ which would roughly correspond to a distribution $\propto a^{-1.5}$, i.e. somewhat smoother than the range considered by us. Yet, it is very likely that penetrating encounters with molecular clouds have contributed to the depletion of the outer layers of the Oort cloud, thus leading to a steeper decrease in the number of comets with a, i.e. a larger value of the exponent α (in absolute value).

The steady flux of new comets with $q < q_e$ produced by the combined effect of stellar perturbations and the tidal force of the galactic disk will be given by

$$\dot{n}_{steady} = \int_{a_{fill}}^{+\infty} F_e \frac{1}{P} \Gamma(a) da \tag{10}$$

We note that the observed new comets have original semimajor axes clustered around $a \approx 2.5 \times 10^4 AU$ (Marsden and Sekanina 1973; Marsden et al. 1978). This value turns out to be somewhat smaller than a_{fill}. The question is how Oort cloud comets with $a < a_{fill}$ can reach the Earth region. A possible explanation is that such comets have actually passed before by the region of the terrestrial planets and the Jupiter-Saturn region where their semimajor axes were slightly decreased below a_{fill} by planetary perturbations. After returning to the Oort cloud they also decreased their perihelion distances by the action of stellar perturbations and galactic tides to values smaller than a few AU so they become observable in their next return. In this manner we can see Earth-approaching comets with original semimajor axes somewhat smaller than a_{fill} that are not "new" in a strict sense.

4. Sporadic perturbers – Comet showers

Since a sporadic perturber – a very close stellar passage or a molecular cloud – affects the inner portions of the Oort cloud where loss cones are empty, the effect will be their sudden refilling. Comets falling within the Earth cone will reach the Earth orbit in a time scale on the order of the orbital period P, thus causing a sudden increase in the influx rate of new comets.

Let us now estimate the volume of the Oort cloud within which the loss cones will be refilled due to a close stellar passage. The impulse received by the comet C (Fig.3) is approximately given by

$$\overrightarrow{\Delta v} \sim \overrightarrow{\Delta v_c} = \frac{2GM}{VD} \frac{\mathbf{D}}{D} \tag{11}$$

where M is the mass of the star, V its relative velocity with respect to the Sun (and the comet) and D is the distance of closest approach to the comet. Let us adopt a reference system centered on C with the x-axis parallel to the stellar path and the xy plane containing the radius vector $\mathbf{r}$. Let us define the angles β and θ as those formed by the vectors $\mathbf{r}$ and $\mathbf{y}$, and $\mathbf{D}$ and $\mathbf{z}$, respectively. Then, the transverse component Δv_T will be given by

$$\Delta v_T = \Delta v (1 - \sin^2\theta \cos^2\beta)^{1/2}, \tag{12}$$

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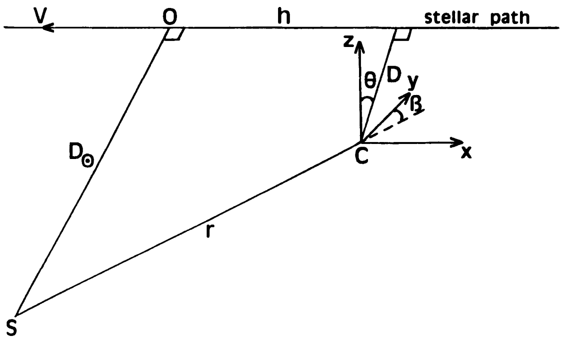

Fig. 3. Geometry of a close star's passage. S: Sun, C: comet. r is contained in the plane xy.

where $\cos\beta \simeq D_\odot/\mathrm{r}$. From now on we assume that $D << D_\odot$.

There will be a region along the star's path where the loss cones of Oort cloud comets at heliocentric distances $r \sim (D_\odot^2 + h^2)^{1/2}$ will be refilled. This region will be narrow around the point O of closest approach of the star to the Sun (i.e. for $h = 0$) and will broaden as h increases. Let us consider those comets confined between the planes perpendicular to the star's path at distances h and $h + dh$ to O. The particular subset at distances $D \leq D_L$ to the stellar path, where $D_L = f(h, \theta)$, will get totally refilled. By combining eqs.(4),(11) and (12) we obtain

$$D_L = (2/3)^{1/2}(M/M_\odot)(V_L/V)(h^2 + D_\odot^2 \cos^2\theta)^{1/2}, \tag{13}$$

where $V_L = (GM_\odot/q_L)^{1/2}$. The flux of new comets with $q < q_e$ produced by the star's passage will be given by

$$\dot{n}_{close} = 2\int_0^{2\pi}\int_0^{h_{max}}\int_0^{D_L}\gamma(r)\,D\,dD\,d\theta\,F_e\,\frac{1}{P}\,dh, \tag{14}$$

where $\gamma(r) \propto r^{-(\alpha+2)}$ is the number density of Oort cloud comets. $h_{\max}$ can be taken as infinity without too much error.

A star passing at a closest distance to the Sun D_m will perturb Oort cloud comets of semimajor axis $a \approx D_m$. The corresponding enhancement in the flux of new comets caused by the star's passage will have an intense phase of a duration on the order of $P = a^{3/2} \approx D_m^{3/2}$. Stars will pass at a closest distance to the Sun D_m parsecs at average intervals

$$\Delta t = \frac{1}{2n_* D_m^2} \simeq \frac{0.071}{D_m^2} Myr. \tag{15}$$

For instance, from eq.(15) we should expect a close encounter at $D_m \approx 10^4 AU$ every ≈ 30 Myr. This result turns out to be somewhat smaller than the one derived by Weissman (1991) of about 50 Myr, but the difference cannot be considered as very significant. Shower comets produced by a close stellar passage will have their aphelion points clustered in a sky area along the stellar path and in particular toward the point of closest approach of the star to the Sun.

Interstellar molecular clouds may be other sporadic perturbers of importance in the dynamical history of the Oort cloud. Their dynamical influence was addressed by Biermann (1978) and afterwards by Napier and Clube (1979) and Napier and Staniucha (1982) among others. More elaborated treatements were performed by Bailey (1983) and Hut and Tremaine (1985). Let us consider a penetrating encounter of the Sun with a molecular cloud, assumed to be spherical and of uniform density, radius R_{cl} and mass M_{cl}. The impulsive change in the velocity of a comet at a distance r to the Sun is (Biermann 1978)

$$\Delta v_{cl} = \frac{2GM_{cl}}{v_{cl}} \frac{r}{b^2} \left[1 - \left(1 - \frac{b^2}{R_{cl}^2} \right)^{3/2} \right] \sin \eta, \tag{16}$$

where $v_{cl} \approx 20 kms^{-1}$ is the typical encounter velocity with molecular clouds, b is the impact parameter and η is the angle between $\mathbf{r}$ and $\mathbf{v}_{cl}$.

The most devastating effects will occur when the solar system encounters a giant molecular cloud (GMC), typically of a mass $M_{cl} \approx 5 \times 10^5 M_\odot$ and radius $R_{cl} \approx 20$ pc. According to Bailey (1983), the number of such encounters could be in the range $1 - 10$ during the solar system lifetime (see also Talbott and Newman 1977; Torbett 1986). Penetrating encounters with intermediate-size molecular clouds, with masses of a few $10^3 - 10^4 M_\odot$, will be more frequent although less dramatic. The number density of these clouds may be about two orders of magnitude greater than that of GMCs (Drapatz and Zinnecker 1984), so that a penetrating encounter of the solar system with an intermediate-size molecular cloud might occur at average intervals of several 10^7years.

The fraction f of loss cone filled with comets due to a penetrating encounter with a molecular cloud will be obtained substituting in eq.(4) Δv_T by $(\Delta v_{cl})_T = \Delta v_{cl} \cos \eta$. By taking an average $< \sin^2 2\eta >= 8/15$, we will obtain a limiting semimajor axis, a_{cl}, for which $f = 1$. Thus, the influx rate of Oort cloud comets due to this perturber will be given by

$$\dot{n}_{cl} = \int_{a_{cl}}^{a_{fill}} F_e \frac{1}{P} \Gamma(a) da. \tag{17}$$

5. Intensity and duration of a comet shower

The fluxes of new comets produced by different perturbers have been obtained from eq.(17) and are shown in Table 1. They have been normalized in such a way that the one produced by the combined action of the steady perturbers is taken as unity. As shown, the relative importance of each one of them varies with the degree of central condensation of the Oort cloud (expressed by different values of the index α). For a heavily concentrated Oort cloud (say, $\alpha = 4$), a close stellar passage at $D_\odot \approx 10^4$AU can trigger a comet shower with a frequency of passages during its phase of highest intensity $\approx 10^2$ greater than the background flux. The same effect can be reached with an encounter with a GMC. Less concentrated models of the Oort cloud (say, $\alpha = 2 - 2.5$) will give rise to showers only about ten times as

TABLE I
Influx Rate of Oort Cloud Comets in Earth-crossing Orbits

	α	2.0	2.5	3.0	3.5	4.0
Steady Perturbers	Background Stars.	0.45	0.40	0.36	0.32	0.29
	Vertical Galactic Tides.	0.55	0.60	0.64	0.68	0.71
		1.00	1.00	1.00	1.00	1.00
Sporadic Perturbers	Intermediate-Size Molecular Cloud.	3.9	4.7	5.9	7.0	9.4
	GMC	27.9	45.1	72.5	116.5	188.0
	Close Star Passage ($D_\odot = 10^4$ AU).	5.4	11.4	24.1	50.9	106.8

intense as the background comet flux. We note that even closer stellar passages at, say $D_\odot \simeq 5000AU$, might have triggered comet showers as intense as about 10 – 40 times the showers triggered by an encounter at $D_\odot \simeq 10^4 AU$, again depending on the degree of central condensation of the Oort cloud. Stellar encounters at distances of $\approx 5000AU$ should be expected at average time intervals on the order of $1-2\times10^8$ years.

Monte Carlo models carried out by Heisler et al. (1987) and Heisler (1990), that incorporate both stellar and galactic tide perturbations, show very nicely the production of comet showers at average intervals of several 10^7 years (see Fig.4). As Heisler's numerical results show, for $a = 10^4 AU$ 98.6% of the comets with $q < 2AU$ will enter during showers. For $a = 2 \times 10^4 AU$ this percentage decreases to 34%, whereas for $a = 3 \times 10^4 AU$ the showers are clearly missing indicating that the loss cone is full.

The intense phase of a comet shower will last a time of the order of $P = a^{3/2}$years, where a is the typical semimajor axis of shower comets. After that the intensity will drop drastically, though a long tail of residual shower comets will still be present before the comet flux reaches the quiescent (background) level. Numerical simulations carried out by Hut et al. (1987) and Fernández and Ip (1987) confirm this behavior (see Fig.5). The tail of residual comets can stretch for 20 – 30 Myr, so that it is possible that features pointing to past strong perturbations of the Oort cloud, appearing as aphelion clusterings (e.g. Biermann et al. 1983), may usually be present.

Shower comets with long dynamical time scales come from those initially in trans-jovian orbits, i.e. filling the outer portions of the loss cone. After a passage,

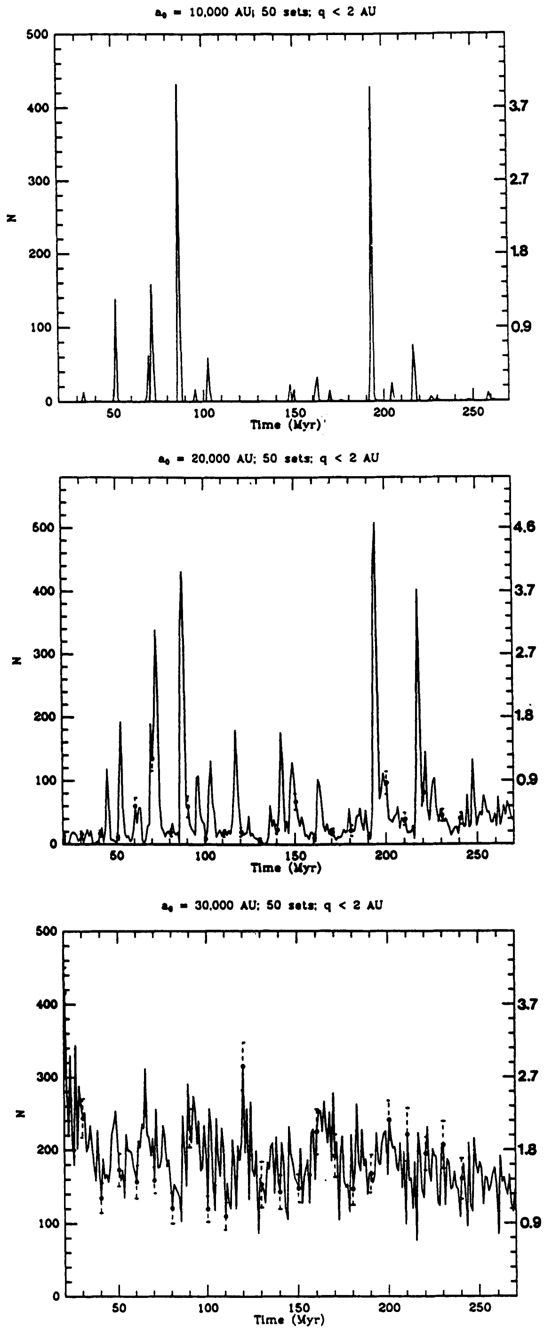

Fig. 4. Monte Carlo simulations of comet showers from Heisler (1990).

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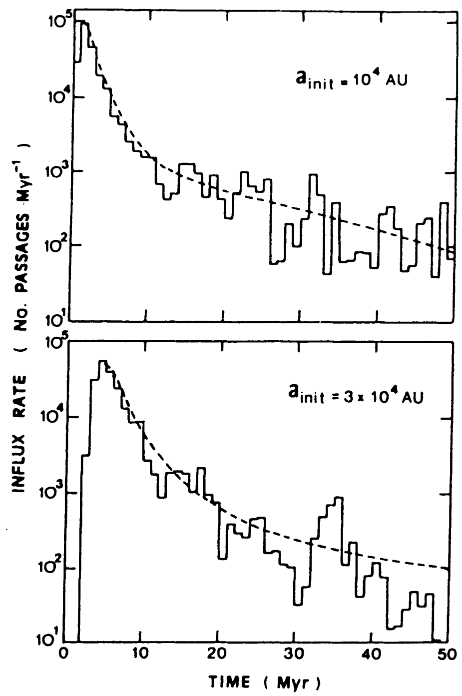

Fig. 5. Numerical simulations showing the time evolution of comet showers after injection of 10^5 hypothetical comets from Fernández and Ip (1987).

a fraction of these comets will return to the Oort cloud where they are perturbed by passing stars and galactic tides that slightly change their q. This process may be repeated several times,thatisthecapturedcomets will "bounce" back and forth between the planetary region and the Oort cloud. A fraction of them can finally reach the Earth zone in time scales going from several Myr to a few tens Myr.

6. Do comet showers reflect in the impact cratering record?

Bailey (1990) argues that Earth-crossing asteroids dominate the terrestrial cratering rate at all sizes. These results depend of course on the magnitude distribution of a given class of objects, the mass-magnitude relation and the crater-diameter scaling laws. He gives an equation for the overall cratering rate

$$\dot{N}_{obs}(\geq D_c) = (3 \pm 2) \times 10^{-6} D_{20}^{-\nu} yr^{-1}, \tag{18}$$

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where $\nu \simeq 2.0 \pm 0.2$ and $D_{20} = D_c/20$ km. If we take $D_c = 10km$, we obtain a total production of about 6000 craters $> 10km$ over a period of 500 Myr. The sample of well-dated craters formed during this period is scarcely $\approx 0.5\%$ of this number.

From the lunar cratering rate we would obtain a terrestrial cratering rate ≈ 3 times smaller than that obtained from eq.(18). An explanation would be that most crater-forming projectiles have relatively small approach velocities to the Earth, thereby enhancing the gravitational focusing factor for the Earth compared to the Moon. This can be understood if Earth-crossing asteroids rather than LP comets now dominate the Earth-Moon cratering flux. Models by Bailey (1990) suggest that comets make less than 10% of the observed terrestrial craters, a result that would be strengthened if the overall cometary masses were reduced by, say, one order of magnitude. Any model in which observed LP comets make a significant contribution to the steady-state terrestrial cratering rate would imply an outer Oort cloud mass $> 100 M_{\oplus}$.

Weissman (1990a) estimates that cometary showers account for approximately 17% of terrestrial craters $> 10km$ diameter, versus the steady-state flux of long- and short-period comets that provides about 12% of the cratering flux. The cratering rate on the Earth from the currently observed flux of Earth-crossing objects – asteroids and comets – is found to be

$$2.2 \times 10^{-14} km^{-2} yr^{-1}$$

that agrees well with the cratering rate over the past 600 Myr estimated by Shoemaker (1977) and Grieve (1984) and the value derived from eq.(18).

The question is how intense should a comet shower be to reflect in crater statistics. Let $\dot{N}_s$ be the steady-state cratering rate on the Earth from Earth-crossing objects. Let $\dot{N}_{sh}$ be the time-dependent cratering rate due to the comets coming in a shower. If we assume that close stellar passages at, say $D_{\odot} \approx 10^4$AU, are the main cause of comet showers, then they may occur at average intervals of $\Delta t \approx 30$ Myr. The duration of a comet shower – at least during the intense phase – is of the order of the orbital period of shower comets, typically of about $T_{sh} \approx 1$ Myr. The number of craters produced during a comet shower should be at least comparable to the background craters produced during Δt. Otherwise we will tend to pick mostly background craters which will tend to blur possible clusterings in crater ages caused by impacting shower comets, i.e.

$$\dot{N}_{sh} \times T_{sh} \sim \dot{N}_s \times \Delta t. \tag{19}$$

Now, the contribution of comets to the steady-state cratering rate is about 10%, namely $\dot{N}_c \approx 0.1 \dot{N}_s$. Substituting this value into eq.(19) we get

$$\dot{N}_{sh} \sim 300 \dot{N}_c. \tag{20}$$

Therefore, the intensity of the comet shower should be at least about 300 times greater than the steady-state comet flux to show up in crater statistics of small samples. As seen in Table 1, close stellar passages are not able to trigger such intense comet showers at intervals of a few tens Myr, so it seems very dubious the claims about possible periodicities in the impact cratering rate.

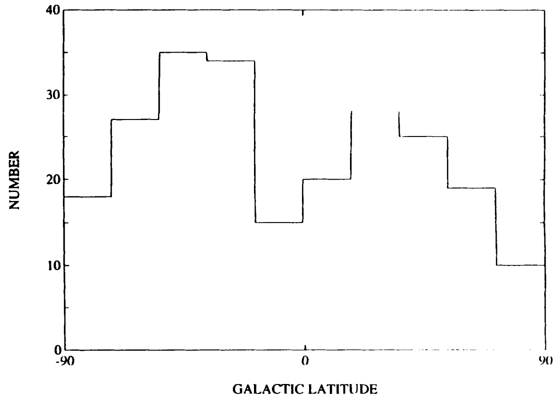

Fig. 6. Number of Oort cloud comets in equal-area strips of the celestial sphere parallel to the galactic equator. The histogram contains a sample of 231 less-evolved *LP* comets whose aphelion directions are estimated to have changed by less than an average of 5 degrees from their primordial directions (Gallardo 1991).

Weissman (1985) has argued that most of the compositions of the impacting bodies, identified from analyses at the impact sites, are more consistent with an asteroidal source for the projectiles rather than a cometary one. More recently the same author (Weissman 1990*b*) has reanalyzed a larger sample of well-dated craters with diameters $\geq 10km$ and does not find any evidence of clusterings of crater ages attributable to comet showers. As mentioned above, this sample is still too small to reveal weak crater-age clusterings attributable to past very intense comet showers occurred over time spans of 500 Myr or so.

7. The current passage rate of Oort cloud comets: does it represent a quiescent stage or an excited one?

The steady supply of Oort comets as due to the dominant action of tides of the galactic disk will produce a distribution of aphelion points concentrated at mid-galactic latitudes. On the contrary, comet showers will not show such a galactic dependence; in particular, Oort cloud comets injected into the planetary region by a close stellar passage will have their aphelia clustered along the star's path.

The observed aphelion distribution of new and dynamically young comets follows a pattern reflecting the influence of the galactic disk potential with a maximum at mid-galactic latitudes (see Fig.6). This was already noted by Byl (1983) and analyzed further by Delsemme (1987). The evidence that most new comets seem to be deflected to the inner planetary region by galactic tides – a steady perturber – suggests us that the frequency of comet passages is at present close to its bottom level (Fernández and Ip 1991). Comets injected during a shower might greatly exceed the steady supply of Oort cloud comets, brought mainly by galactic tides, in such a way that the galactic dependence in the distribution of aphelion points could be severely weakened. Indeed, there are some weak aphelion clusterings that might reflect past close stellar passages, though they seem to be a minor fraction of the overall aphelion sample.

Heisler (1990) poses the apparently puzzling question that the distribution of reciprocal semimajor axes of new comets shows a concentration at $1/a \approx 75$ (in units of $10^{-6} AU^{-1}$) which is in contradiction with what we should expect of Oort cloud comets driven into the inner planetary region by the combined action of stellar perturbations and galactic tides; for these the concentration should be centered at $1/a \approx 30$ (cf. Section 3). Heisler argues that this discrepancy could be attributable either to the occurrence of a weak shower or to errors in the determination of $1/a$ and/or contamination with older comets. We recall that a close stellar encounter in the near past would produce shower comets with rather small values of a, say $a \approx 10^4 AU$ or $1/a \approx 100$ in the above units.

The other possibility is that "new" comets with $50 \lesssim (1/a) \lesssim 100$ may actually be repeating passages through the planetary region as we showed in Section 3. An inspection of Fig.1 shows that when we limit the sample to new comets with $q > 2AU$ – for which errors caused by nongravitational forces and contamination by older comets are possibly less dominant – the concentration shifts to the range $20 < (1/a) < 50$. This strengthens the view that the truly "new" comets currently come from the Oort cloud region where steady perturbers – mainly galactic tides – play a dominant role. Consequently, the comet flux should currently be at or near its background level with little contribution from comet showers.

8. Conclusions

Comet showers as intense as about 10 – 100 times the background comet flux can occur at average intervals of some 10^7 years. The intensity of the comet shower will depend on the degree of central condensation of the Oort cloud. The main trigger mechanism may be very close stellar passages, say at distances of about $10^4 AU$, though penetrating encounters with intermediate-size molecular clouds might be of some significance. Even closer stellar passages, say at distances of a few $10^3 AU$, or penetrating encounters with GMCs may cause more intense comet showers of some $10^2 - 10^3$ times the background comet flux at average intervals of a few 10^8 years.

The age-distribution of well-dated impact craters does not show clear indications of clusterings attributable to comet showers. Earth-crossing asteroids and steady-state comets seem to dominate the production of impact craters, so it is difficult to find in small samples of well-dated craters indications of comet showers as claimed by some authors. Perhaps, when much larger samples of crater ages on the surfaces of the Earth and Moon become available, fluctuations of statistical significance attributable to past intense comet showers might be discernible.

The distribution of aphelion points of new and dynamically young comets on the celestial sphere shows a dependence on the galactic latitude, suggesting that tides of the galactic disk play a dominant role in bringing Oort cloud comets into the inner planetary region. On the other hand, strong aphelion clusterings are not observed. These observations tend to suggest that we are at present near the background comet flux, since intense comet showers would tend to favor aphelion clusterings and to weaken the galactic signature. Furthermore, the distribution of original reciprocal semimajor axes of new comets with $q > 2AU$ shows a concentration around the range $20 < (1/a) < 50$(in $10^{-6} AU^{-1}$ units) as should be expected if Oort cloud comets are brought into the inner planetary region by stellar perturbations and galactic tides.

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Discussion

H.U.Keller – The aphelia distances of new comets peak at about 40×10^3 AU. After one passage through the inner solar system, the comets should have a $1/a$-distribution with a width of about 5×10^{-4} AU^{-1}. These comets are not reflected in the observed distribution of long-period comets. Where are these comets?

J.Fernández – Half the new comets are lost to the interstellar space by planetary perturbations. As regards to the other half, some may return much fainter, due to the loss of an outer layer of highly volatile material, so that they may pass unobserved. Therefore we are left with a fraction smaller than 50% of comets repeating passages with orbital energies in the range $\sim 5 \times 10^{-4}$ AU^{-1} that can be detectable. This basically agrees with observations.

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