EMPIRICAL DATA FROM OORT'S CLOUD

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ABSTRACT. Empirical evidence about the size and the origin of the Oort's cloud of comets is confronted with theories about its origin. The slow diffusion of the orbits of the "new" comets into the inner solar system implies a redefinition of the concept of "new" comet. A gradual transfer of orbital angular momentum occurs from the planets to the comets as the comets grow older on shorter period orbits. The observed retrograde to prograde ratio of the new comets is difficult to explain. Either it comes from a poorly understood observational bias, or from a neglected secular action of the Galaxy, or it implies a recent asymmetrical perturbation of the Oort's cloud (less than 10-20 million years ago). The grazing incidence of a giant molecular cloud or an exceptionally close stellar passage would introduce such an asymmetry; this would also be true for the unseen hypothetical stellar companion of the Sun recently invoked to explain the periodicity of the geological extinction of species through violent cometary showers.

1. INTRODUCTION

A renewed interest in the elucidation of the origin of comets is apparent in the literature of the 1980's. Besides the classical approach which links the origin of the Oort Cloud with that of the solar system, alternate theories have multiplied recently, as is also clear from a number of other papers in this Colloquium.

This is a healthy situation. However, it is important not only to remember the empirical data that are related to the problem, but also to take them into account inasmuch as it is possible, even if they are scanty, because they may be used as bounds to limit the possibilities, or as criteria to compare models.

I have discussed in the past several sets of empirical data that are relevant to the "new" comets (Delsemme 1977, 1979, 1983). I will first mention them shortly; I will then explore a new set of data, that are relevant to the possible orbital angular momentum of the Oort's cloud.

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2. THE DIFFUSION OF NEW COMETS INTO THE PLANETARY SYSTEM

The first set of observational data comes from the statistics in the binding energy (per unit mass) of the very long period comets. We have now a list of two hundred and twenty long-period comets whose original orbits are known with accuracy. The most complete list is given in particular by Marsden and Roemer (1982) and is based mainly on the work of Marsden and Sekanina (1973) and Marsden, Sekanina and Everhart (1978). They have also shown that whatever the reason, the effective distance of the outer margin of the Oort's cloud is best established by the extrapolation of the binding energies of "new" comets with larger perihelion distances, that is, with smaller non-gravitational forces (NGF). They find that the extrapolated mean binding energy is $1/a = 46$ (in 10^{-6} AU^{-1}) and the scatter is only ±10. This corresponds to an effective margin extending nominally between 35,700 AU and 55,600 AU, with a mean distance of $2a = 43{,}500$ AU. This does not mean that Oort's mechanism does not work any more at 200,000 AU, but only that aphelia in that zone do not make a significant contribution. Oort (1950) had found 220,000 AU for the same outer margin, but this was from poor statistics based on ten orbits with $1/a < 50 \times 10^{-6}$ AU^{-1}, also ignoring the variable influence of NGF.

The fact that the Oort's cloud is five times as small as believed before has important consequences that have not escaped the attention of recent authors (Bailey 1977, Weissman 1978). The major consequence is that the mean velocity perturbation ΔV_{RMS} introduced by stellar passages is smaller than Oort believed. Using Oort's (1950) approach with proper numerical changes, I find a formula which is almost the same as that agreed with by most authors (Faintich 1971; Weissman 1982):

$$\Delta V_{RMS} = 1.8\ T^{1/2}\ (\text{in m s}^{-1}) \tag{1}$$

where T is the duration of the perturbation in millions of years. With a mean 2a = 43,500 AU, the mean period of a new comet is 3.2 M yrs, with no more than 3M years spent in the outer margin of the Oort's cloud. Therefore the ΔV_{RMS} introduced by stellar perturbations is 3.0 m s^{-1} per revolution. The <u>transverse</u> component Δv of that velocity change is only 2.5 m s^{-1} according to:

$$\Delta v = \Delta V_{RMS} \sqrt{\frac{2}{3}} = 0.82 \Delta V_{RMS} \tag{2}$$

The transverse velocity v (at distance r near aphelion) is linked to the perihelion distance q by the formula:

$$v = r^{-1}(2GMq)^{1/2}. \tag{3}$$

Any assumed "new" comet observed with a perihelion q of the order of 1 or 2 AU (aphelion v between 1 and 1.4 m s^{-1}) is therefore unlikely to be a new comet (in Oort's meaning) because on the average, it came from a previous orbit that had been modified only by v = 2.5 m s^{-1}; the perturbation is random in the velocity space, but the largest possible value of the previous <u>mean</u> transverse velocity v_0 is:

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$$v_0 = v + \Delta v \tag{4}$$

which puts its previous mean perihelion at most between 10 and 15 AU. Taking into account its random nature, the velocity perturbation Δv is described by a Gaussian distribution whose mean will be added on the average at a right angle to its original v in the velocity space. For this reason, it is easy to check numerically that an assumed "new" comet with perihelion q = 1 AU has already passed an average of five times through the outer solar system; all these passages took place outside of Jupiter's orbit, the innermost one (before q = 2 AU) being on the average near 8 AU. How then is it possible that most of these new comets still have an unchanged orbital energy, corresponding to the mean distance of the margin of the Oort's cloud?

The answer is that they have really changed. However, the perturbations of Uranus and Neptune are almost negligible; their $\Delta(1/a)$ is of the order of 10×10^{-6} AU^{-1} in most cases, only slightly widening the peak in 1/a of the orbits' distribution (Everhart and Raghavan 1970). Second, most of the recent statistics that have refined our knowledge of the mean distance of the outer fringe of the Oort's cloud, have been derived by giving more weight to those new comets with large perihelia (from 2 to 7 AU); many more of these have indeed come from unperturbed orbits with perihelia beyond Saturn's distance. The original orbits with the smaller perihelia are much more scattered in 1/a as shown by Marsden and Sekanina's 1973 study.

We will therefore accept to change slightly the traditional definition of a "new" comet. From now on, we will call "new" those comets whose binding energies are smaller than 850×10^{-6} AU^{-1}: this is the place in the distribution of all known orbits, where the wing of the peak discovered by Oort becomes conspicuous. Most of these "new" comets are new for us only, since they are usually at their fourth or fifth passage (with larger perihelion distances) through the system of the major planets. However, all share a major property: before their present passage, they had not yet exchanged much energy or momentum with the planetary system. Those that have, are already beyond our binding energy limit and have therefore been rejected out of the new definition.

Is there any empirical evidence of this very slow diffusion of the orbits of "new" comets towards the inner solar system? Table I and Fig. 1 represent the ratio N/L of "new" comets N to all long-period comets L as a function of their perihelion distance. The very fact that the ratio N/L climbs from 11% (within 0.8 AU) up to 81% (from 3 to 7 AU) is a strong empirical evidence that the previous discussion is right. The major jump on Fig. 1 takes place from 1.8 to 3.0 AU; it can be interpreted by the fact that previous perihelia of those comets (now near 3 AU) were beyond 10 AU and were therefore undisturbed by the major perturbations of Jupiter and Saturn. There is no observational bias that could be large enough to explain away the large statistical difference (a factor of eight) that is apparent in the N/L ratio, from 0.8 AU to more than 3 AU.

Another empirical evidence comes from the fact that the vaporization dependence on distance, observed for new comets, is the same as

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that for older comets: they are all controlled by the sublimation of water ice (Delsemme 1983); the nine "new" comets studied so far all have perihelion distances smaller than 1.5 AU; therefore, they are likely to have all had previous perihelion passages at a distance where any material more volatile than water would have already been lost.

TABLE I

Ratio N/L of the New Comets to all Long-Period Comets, Versus their Perihelion Distance q

q in AU	L	N	N/L	
0 - 0.8	271	30	11%	
0.8 - 1.2	158	24	15%	
1.2 - 1.6	60	13	22%	
1.6 - 2.0	30	14	47%	
2.0 - 3.0	39	20	51%	
3.0 - 7.0	31	25	81%	
0 - 7.0	589	126	21%	TOTAL

N means the number of NEW comets within each q interval. L is the number of all LONG-PERIOD comets, including new comets, within the same interval.

3. A BIMODAL DISTRIBUTION FOR "NEW" COMETS

The second set of data is about the brightness distributions of the "new" comets (Delsemme 1979); it is bimodal, presumably separating pristine comets from the other ones: 82% have a brightness distribution peak near absolute magnitude 5.5 (presumably, the true "new" comets), whereas 18% show a peak near absolute magnitude 10 (presumably, long period comets that have lost their original brightness by fragmentation). Incidentally, in my Table I page 267 (Delsemme 1979) a copying mistake has put Comet 1932 VI in the 9.1 to 10 line; it should be moved to the 3.1 to 4 line; this brings the number of fragmented comets from 19% to 18%.

The shape of the distribution of the true "new" comets implies that their formation mechanism has not been influenced by fragmentation: their brightnesses imply a nuclear radius from 5 to 1 km, with an average of 3 km. They match the size predicted by Goldreich and Ward (1973) from gravitational instabilities in the protosolar nebula for those planetesimals accreting near the terrestrial planets, but not in the zone of Uranus and Neptune where it is usually assumed they were born. However, the settling of dust was not necessarily homologous in the solar nebula, and the numerical mismatch cannot be construed as an argument against this type of origin. The essential fact of this discussion is that the observed size distribution suggests a straightforward accretion without later fragmentation.

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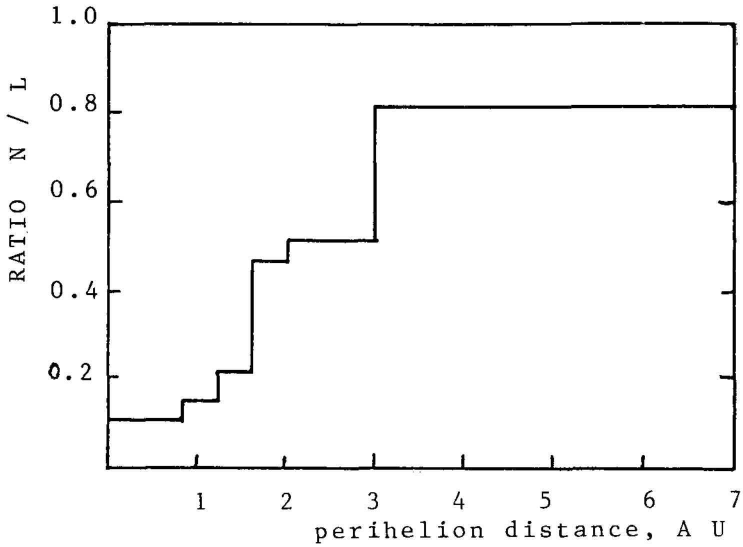

Fig.1.- Ratio of the New (N) to the long-period (L) comets.

4. RETROGRADE VERSUS PROGRADE ORBITS

The third set of data, relevant to the rotation of the Oort's cloud, must be introduced first by showing the observed regularities in cometary orbits. We all know that the short-period comets turn in the prograde direction; it is also conventional wisdom to state that the long-period comet orbits have a more or less isotropic distribution in space. In Table II we have refined somewhat this description, by using Marsden's (1983) Catalog of Cometary Orbits to classify all comets into subsets, mostly according to their periods.

According to our new definition, line (7) lists as "new" those long-period comets whose orbits were known accurately enough to compute original orbits with an $1/a \leq 850$ (in 10^{-6} AU^{-1}); they include the residue of (weakly) hyperbolic comets and they probably contain a very large proportion of really new comets. A few very-long-period comets present in line 6 are duplicated in lines 4 and 5, since we did not use the original orbits for those two lines. However, the general trend is clear: the ratio R/P (retrograde over prograde number of orbits) varies monotonically as a function of the mean period of each subset (see Fig. 2). The interpretation of this is also obvious: statistically speaking the more the comets have exchanged energy with the planets, the more they have exchanged angular momentum.

In Table II, the group of poorly defined parabolic comets is not very useful because it is ambiguous: they are listed as having parabolic orbits, either because no deviation from a parabola can be detected, or because the appropriate calculations have not been made. One of the major reasons for this situation is that the observed arc may not be long enough. For parabolic comets passing close to the sun, there is therefore a differential Holetschek(1891) effect. The

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TABLE II

	COMETS	PERIOD, YEARS	TOTAL	PROGRADE	RETROGRADE	RATIO R/P
(1)	Short p.	$3<P<20$	104	104	0	0.00
(2)	Interm. p.	$20<P<200$	17	13	4	0.31
(3)	Long p. I	$200<P<1000$	37	24	13	0.54
(4)	Long p. II	$10^3<P<10^4$	101	56½	44½	0.79
(5)	Long p. III	$10^4<P<10^5$	43	23	20	0.87
(6)	Long p. IV	$10^5<P$, & hyperbolic	139	74	65	0.88
(7)	"New"	----	126	65	61	0.94
(8)	Poorly defined "parabolic" orbits		312	170	142	1.20
(9)	General totals:		879	529½	349½	0.66

(3) Five long-period I orbits have almost identical elements; this well-known sungrazing group has been assumed to come from one comet that has recently split, and counted for one in the statistics.
(4) Comet 1970 II, with an inclination of 90.0°, was counted for ½ in the prograde and ½ in the retrograde columns.
(5) The long-period I, II and III are taken straight from Marsden's Catalog. Group II and mainly Group III contain already a few "new" comets.
(6) Group IV contains many "new" comets.
(7) The "new" comet list is from Marsden and Roemer (1982) with a cutoff at $1/a=850\times10^{-6}$ AU^{-1} (see text for discussion).
(8) The 5 identical sungrazing comets have only been counted for one. The differential Holetschek effect probably explains the large R/P ratio of this group.
(9) The general totals are not very meaningful, because the duplication of group (7) has not been removed from the totals.

differential Holetschek effect between prograde and retrograde parabolic comets comes from the Earth's motion on its orbit: since prograde comets turn in the same direction as the Earth, on the average they are hidden by the sun's glare longer. The effect is maximal for q/cos i = 0.7 AU because the perihelion apparent angular velocity component along the ecliptic matches the Earth's velocity on its orbit; therefore, more comets of this type are in the category of the poorly defined orbits, which fall into the parabolic bin. The observed excess of retrograde comets classified as parabolic is present but not very important except for short heliocentric distances, where it reaches R/P = 2 between 0.4 and 0.8 AU; this consistency with the qualitative prediction confirms that the retrograde excess probably comes from observational selection. A correction of this observational selection effect could be undertaken (à la Everhart, 1967) but it was judged that it was beyond the scope of this paper.

The previous discussion clarifies the apparent discrepancy that the reader may detect between our results and those of Fernandez in another chapter of this book: the R/P ratio is inverted when ambiguous comets are eliminated from the statistics, and I have shown that we probably understand why.

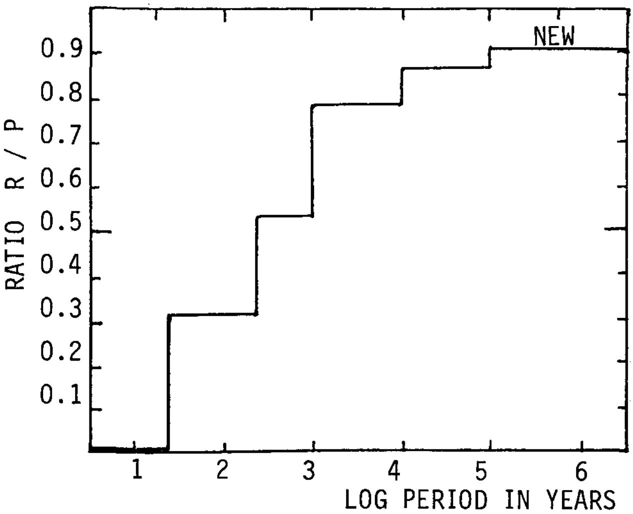

FIG.2.- The ratio R/P of the number of retrograde to prograde comets grows steadily from zero up to 0.94 as a function of their period.

5. THE ROTATION OF THE OORT'S CLOUD

If we accept the conventional wisdom that short-period comets derive from the orbital diffusion of "new", then of long-period comets, the smooth but steady orbital angular momentum transfer from the planets to the comets shown in Table II and Fig. 2 comes in step with the random transfer in binding energy, with a difference: the change in binding energy is a random walk, whereas the momentum transfer, although random in magnitude, is always prograde since it remains on the average in the direction of motion of the interacting planets.

However, the fact that the R/P ratio remains asymptotically near 94%, and does not reach 100% even for very large periods, is puzzling. It cannot be dismissed easily as an observational bias. As a matter of fact, there are more retrograde comets in the small number of "new" comets observed with perihelia beyond 2 AU; this difference is likely to be introduced by the slow diffusion of the orbits described before: retrograde comets are less perturbed than prograde during their passage through the solar system; for this reason, they are kept longer within the 1/a limits that we have arbitrarily accepted to define a "new" comet. However, since this bias is in favor of more retrograde comets, the fact that R/P remains much lower than unity is even more puzzling. Since it seems to remain in the purest possible sample of "new" comets, that have obviously neither exchanged much energy nor rotational momentum with the solar system, could this dissymetry be the telltale of a primeval rotational momentum of the Oort's cloud?

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6. MODELS OF THE SOLAR NEBULA

The classical theories relate the origin of the Oort's cloud to that of the solar system; they vary only in the details about the place of cometary accretion and the mechanism of their ejection into Oort's cloud. Oort's early hypothesis (origin within the asteroid belt) has generally been ruled out because it would yield early temperatures incompatible with the survival of an icy conglomerate nucleus (Whipple 1950); all other distances, starting at Jupiter's orbit, up to a few 10^4 AU have been proposed.

A circular ring of protocometary bodies implies a primordial rotational momentum presumably prograde in the equatorial plane of the protosolar nebula, that is in the ecliptic (for all practical purposes). According to Kepler's third law, its magnitude (per unit mass) would increase with the square root of the ring's radius r.

Of course, the transfer of cometary aphelia to the outer fringe of the Oort's cloud, followed by the growing diffusion of their aphelion velocities (due to the stellar perturbations) is likely to have introduced a Gaussian distribution of velocites with an r.m.s. velocity orders of magnitude larger than the initial aphelion velocity. But this Gaussian distribution of velocities would be centered on a prograde primeval velocity. The question is: could this prograde velocity be detected by the dissymmetry R/P? As can be seen in Fig. 3, the R and the P comets that come back from the Oort's cloud would be from two different heights in the slope of the Gaussian curve: their ratio R/P would be lower than unity, and it would become smaller with larger q's.

To clarify the ideas, we have compared the small-mass models of the nebula, from the Russian School (Otto Schmidt 1949, Safronov 1972-1977) and the large-mass models of the American School (Kuiper 1951 - Cameron 1978-82).

In the small-mass models, Safronov (1972) shows that the comets are planetesimals ejected by the giant planets during their accretion; 100 Earth masses are ejected by Jupiter, 80 by Saturn, 50 by Uranus and 60 by Neptune; but because of the varying efficiency of the process, the mass eventually bound into Oort's cloud is 0.2 Earth masses from Jupiter's contribution, 0.4 from Saturn's, 0.6 from Uranus' and 1.3 from Neptune's. The average weighted distance from which comets were ejected is therefore rather in the vicinity of 30 AU. For a 1 solar mass nebula, the Keplerian velocity at this distance is 5.5 km/s. When ejected at the nominal distance of 50,000 AU, conservation of angular momentum gives a transverse velocity at aphelion of 3.3 m/s.

In the large-mass model, Cameron (1978) has submitted a novel theory on the origin of comets. Using a typical 3 solar mass nebula, it spreads a massive disk at distances going to 300-600 AU. The disk's mass varies with time; after a nominal maximum mass of 2 solar masses, the accretion disk loses half of its mass in $t = 2 \times 10^4$ years, by a photospheric loss mechanism. For those planetesimals whose period is short compared to t, the mass loss inside their orbit enlarges their radius only. However, planetesimals (that is, pristine comets) further away than 500 AU have periods longer than 2×10^4 years. Those for which the mass loss is slightly smaller than a factor of 2 see their

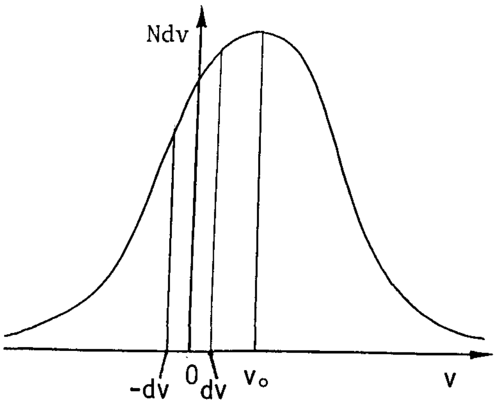

Fig.3. The Gaussian distribution of the transverse velocities v is centered on the velocity v_o of the primordial ring of comets. The slope of the distribution near velocity zero gives an R/P ratio different from unity.

orbits impulsively elongated to those large distances which are now the outer margin of the Oort's cloud, with a perihelion remaining the same (500 AU, typically). If we assume a 3 solar mass nebula, the 500 AU ring of comets turns with a Keplerian circular velocity of 2.3 km/s, yielding 23 m/s when at the nominal aphelion in the Oort's cloud.

The two scenarios yield two Oort's clouds with a different primeval momentum, that we have expressed by 2 different transverse velocities at the nominal (and arbitrary) distance of 50,000 AU. (See Table III).

In Cameron's case, the primeval cloud remains a ring. In Safronov's case, planetesimals are ejected by their grazing passages near the giant planets on hyperbolic orbits (related to the planet's center of mass), going to all directions. At an average of 30 AU, the orbital momentum transfer per unit mass goes from 0 to 2V (V= 5.5 km/s). The mean orbital momentum transferred by planetary interaction gives an average extra 1 m/s in the prograde direction at 50,000 AU.

In both cases, during 4.5 billion years, stellar random perturbations scatter the velocities according to a Gaussian distribution following formula (1). This yields an RMS velocity of:

$$\Delta V = 121 \text{ m/s}. \quad (5)$$

The RMS transverse component in the plane of the ecliptic is

$$\sigma = \Delta V \sqrt{\frac{1}{3}} = 0.58\ \Delta V = 70 \text{ m/s}. \quad (6)$$

In RMS units of the present-day distribution, the primeval velocity is 0.33σ (Cameron's model) or 0.06σ (Safronov's model). Translated in terms of R and P for the retrograde and prograde comets that come back from the Oort's cloud within $0<q<7$ AU, we can write $R/P=0.97$ (Cameron's) or 0.995 (Safronov's). These results concern only the velocity components projected onto the ecliptic. In order to compare with the

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TABLE III

The Orbital Angular Momentum of the Oort's Cloud

	Large-Mass Theory	Small-Mass Theory
Major reference	Cameron 1978	Safronov 1972
Mass of disk + sun	3 $m_\odot$	1.04 $m_\odot$
Mean radius of protocomets' ring	500 AU	30 AU
Keplerian velocity of ring	2.3 km/s	5.5 km/s
Transverse velocity at 50,000 AU	+23 m/s	+3.3 m/s
Extra velocity due to ejection	0	+1.0 m/s
Primeval velocity in Oort's cloud	+23 m/s	+4.3 m/s
Δv (RMS) in ecliptic (from stars)	±70 m/s	±70 m/s
Primeval velocity in RMS units	0.33σ	0.06σ
Predicted R/P for observed "new" comets	0.97	0.995

observations and reduce somewhat the noise coming from the transverse velocity component which is not in the ecliptic, I have also projected the transverse velocity onto the plane of the ecliptic for each of the 126 new comets, according to the formula:

$$v_e = v(1-\cos^2\omega \sin^2 i)^{1/2}. \qquad (7)$$

v_e is the transverse velocity projected on the plane of the ecliptic, v is the transverse velocity of the comet, ω is the argument of its perihelion and i the inclination of its orbit.

The 126 transverse velocities projected onto the ecliptic v_e have been classified in the histogram of Fig. 4. To understand the significance of the histogram, a transverse velocity of 2.24 m/s brings the comet's perihelion at the distance of Jupiter's orbit. The well documented depletion for short heliocentric distances is quite apparent near $v_e = 0$. Assuming that the asymmetry of the data comes entirely from the slope present in the Gaussian distribution of the velocities (see Fig. 3) it is concluded that this Gaussian distribution is superimposed on a mean orbital momentum of 152 m/s at the nominal distance of 43,500 AU. The simpleminded use of dN/N = 6% excess of retrograde comets already gives a good approximation of this orbital momentum, very close to the same value. Expressing the number of comets of velocity v by the Gaussian formula:

$$N\,dv = \exp(-\tfrac{1}{2}\,\frac{v^2}{\sigma^2})dv \qquad (8)$$

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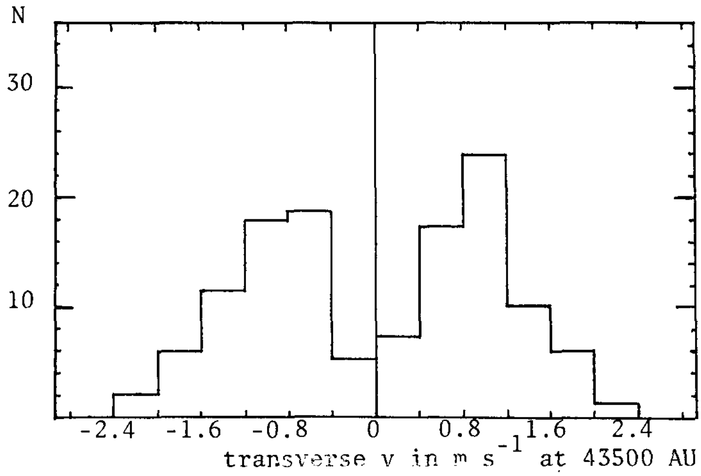

Fig.4.- Number N of new comets classified by transverse momentum intervals.

the logarithmic differentiation gives:

$$-\frac{v}{\sigma} = \frac{dN/N}{dv/\sigma} \qquad (9)$$

with dv = 1.9 m/s between the mean prograde and mean retrograde velocity of our sample, and σ = 69.4 m/s for the transverse r.m.s. component over the age of the solar system, dv/σ = 0.027 and dN/N = 0.060, yielding v = 2.22 σ or 154 m/s.

DISCUSSION

First, it seems prudent to remove from the sample all comets whose perihelion is close to the orbit of Jupiter. In a computer simulation, Fernandez (1981) has shown that at Jupiter's distance, the perturbation on prograde orbits is (statistically speaking) six times larger than on retrograde orbits. The net result is that prograde orbits have been removed from the narrow range in binding energy that defines "new" comets, six times more effectively than retrograde orbits, introducing an unwanted bias.

Since the transverse velocity corresponding to Jupiter's orbit is 2.24 m/s, if we use a cutoff of 2.00 m/s for v, we lose only three comets (one prograde and two retrograde, as would be expected from Fernandez' results). We are left with 123 "new" comets with R/P = 0.92, that is an 8% asymmetry in favor of the prograde direction for new comets. Table IV shows the final results. The oddity of the result is reinforced by the fact that Fernandez' (1981) mechanism, applied to all outer planets, predicts a larger depletion of prograde comets than of retrograde comets. We conclude that the original R/P is even

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smaller than 0.92.

Are the results statistically significant? Because of the small numbers involved, the chances that the asymmetry is in favor of the prograde direction are only about 2 to 1. However, when the probabilities are computed for each speed interval, then multiplied, the total probability in favor of the prograde direction grows to 75%.

TABLE IV

Retrograde/Prograde ratio of the "new" comets, as a function of their transverse velocity component v_e projected onto the plane of the ecliptic.

v_e ms^{-1}	Prograde	Retrograde	R/P
0 -0.4	7	5	0.71
0.4-0.8	17	19	1.12
0.8-1.2	24	18	0.75
1.2-1.6	10	11	1.10
1.6-2.0	6	6	1.00
2.0-2.4	1	2	2.00
Total	65	61	0.94

Can the results be biased by an observational selection? We have mentioned a differential Holetchek effect that could explain the excess of retrograde comets. This observed excess is serious only for small perihelion distances, as predicted by its interpretation. An inverse differential effect is therefore predicted for the "good" orbits (those not classified as parabolic). But at short perihelion distances, the number of "new" comets (retrograde or not) is severely depleted, as are all comets (Everhart 1967). For this reason, the inverse differential Holetchek effect should be practically negligible for the "new" comets. It is concluded that the spurious excess of quasi-parabolic comets on retrograde orbits introduces an insignificant bias for new comets.

Let's assume therefore that the observed asymmetry of at least 8% is real. It is incompatible with a primordial rotational momentum due to a ring of protocomets at 30 AU (R/P = 0.995) or at 500 AU (R/P = 0.97). Because of the uncertainties due to small number statistics, it could be more easily consistent with Cameron's model than with Safronov's. However, a primordial ratio R/P = 0.94, taken at its face value, would rather be suggestive of a very massive protosolar nebula or of a nebular satellite of the protostar system. In such a dense nebular satellite, the formation of comets could have taken place on a more reasonable time scale than at the low density of the interstellar medium. Another possibility is Hill's (1982) mechanism: in presence of turbulence the infall is no more strictly radial (Cameron 1984).

Another possible interpretation is that the detected rotational momentum is real but not primordial, it would be connected to a recent

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non-radial impulse upon the cloud of comets. The observed "new" comets have had their perihelion lowered into the inner solar system during their last 3 to 6 orbits only ($\Delta v = 2.5\ ms^{-1}$ per orbit), that is during the last 10-20 million years. This gives the time scale for a "recent" impulse. Three distinct possibilities fall into this category: a giant molecular cloud, the close passage of a foreign star, or an unknown stellar companion of the Sun.

First possibility: each passing star produces a small non-radial impulse; it is only because of the large number of stars (more than 25,000) that have randomly influenced the Oort's cloud in the last 4.5 billion years, that we speak about a symmetrically Gaussian distribution of velocities within the cloud. However, during the last 10-20 million years, we deal with a population of 50-100 perturbing stars only, and the very large influence of one single close stellar encounter becomes a serious possibility. Biermann, Huebner and Lust (1983) believe that indeed they have identified one star track by aphelion clustering in the Oort's cloud.

Second possibility: following the confirmation of the existence of a system of giant molecular clouds in the Galaxy (Solomon and Edmunds 1980), their passage close to the Solar System has been shown to have an action competitive with that of the nearby stars. The impact of such a molecular cloud at grazing incidence on the Oort's cloud could have introduced all the rotational momentum needed to explain the R/P ratio observed on "new" comets some 10-20 million years later; however, since the number of passages of the Solar System through giant molecular clouds during its lifetime is estimated to be in the range of 1 to 10 (Bailey 1983), the mean duration between passages would be ½ to 2 billion years, and the possibility of a passage during the last 10-20 million years would therefore be of the order of 1%, which makes the hypothesis rather unattractive. For this reason, Clube and Napier (1984) go one step further, opening up vistas on new mechanisms modifying the traditional Oort's cloud concept by cometary captures during passages through "grainy" molecular clouds with a mass structure that plays a fundamental role; a complete discussion of these original ideas is beyond the scope of this paper.

Third possibility: an unknown stellar companion of the Sun, whose 26-28 million year period, on a rather elongated orbit, has been proposed to explain the quasi-periodicity of the mass extinctions of living species on Earth, reported by Raup and Sepkoski (1984). The impact that has produced the major extinction separating the Cretaceous from the Tertiary has now been well substantiated (Bohor et al. 1984) by the existence of shock-metamorphic features of high pressure in quartz grains (duplicated by laboratory experiments at 90 kilobars) and excluding all other hypotheses trying to circumvent an extraterrestrial impact. Since other geologic layers contain the same extraterrestrial concentration (30 to 300 times) of iridium and of heavy metals of the platinum group (Alvarez et al. 1984) sometimes in multiple horizons, there is not much doubt left that there was a multiple impact of several large bodies, concentrated in 10 thousand to 1 million years, and possibly repeated at quasi-periodic intervals of 26-28 million years. Comets are clearly good candidates for this purpose, and the hypothetical stellar companion of the Sun is one of the two mechanisms proposed so far (the frequency of molecular clouds collisions, if modulated by oscillations of the sun around the mid-plane of the Galaxy, is another possibility). Future will tell whether scenarios can be found to offset the inherent orbital instability of the stellar companion of the Sun, over the age of the Solar System (even a circular orbit near 50,000 AU has a survival probability of the order of 1-2%, Shoemaker 1984).

Such a stellar companion would clearly be a good explanation for the asymmetry R/P, since it would have transmitted its last impulse 11 or 12 million years ago, that is about four "new" comets' periods. A constraint introduced by the wing of the Oort's peak, in the distribution in (1/a), implies that the mean perihelion distance of the companion could not be much less than 10,000 AU. This would imply a quite acceptable aphelion at 170,000 AU to reach the proper period, as well as a transit time of the order of one million years to go across the Oort's cloud.

The scarcity of the data does not allow to choose any further among the different hypotheses that we have discussed here.

On the other hand, the influence of the forces exerted by the Galaxy on the Oort's cloud have been completely neglected in the present paper. We intend to compute soon the other spatial components of the orbital angular momentum of the set of our 126 "new" comets, in order to verify if it could be explained by tidal or epicycle effects in the Galaxy.

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NOTE ADDED IN PRESS

Important developments have taken place in the six months following the Rome meeting: The orbital angular momenta of the 126 new comets show a much larger anisotropy in a plane perpendicular to the ecliptic; it is 54% larger in the retrograde than in the prograde direction. This is too large to come from primordial or galactic effects; it would be dissipated by orbital diffusion in 20-30 million years, hence it must be due to a recent impulsive event. Fast moving bodies (stars or molecular clouds) are ruled out: only a slow body like Nemesis is acceptable. The presumed orbit of Nemesis has been deduced; larger anomalies are found (at the 2σ to 3σ level) along the predicted orbit, over a strip of the sky of 180°, suggesting the place of the perihelion of an eccentric orbit for this massive object. Details will be published at the Tucson colloquium "The Galaxy and the Solar System" (January 1985) and in a letter to "Nature" (Delsemme 1985).

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