Asteroids, Comets, Meteors 1991, pp. 399–402
Lunar and Planetary Institute, Houston, 1992

COMET NONGRAVITATIONAL FORCES AND METEORITIC IMPACTS

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Abstract

We have considered those comets whose original orbits have been determined to be hyperbolic when only planetary perturbations are accounted for. It is found that formally unbound incident trajectories correlate most confidently with orbits that have small perihelion distances and move in a retrograde sense relative to planetary motion. Arguments are presented that these results are not due to measurement error or to selection effects. We conclude that the phenomenon is attributable to enhanced volatility leading to abnormally large nongravitational forces. Since the effect is absent in the prograde small-perihelia population, increased insolation is not the sole explanation. It is suggested that the significance of the retrograde correlation is connected with a larger energy of relative motion between retrograde comets and a population of prograde ecliptic meteoroids which impact the comet mantle exposing the underlying volatiles. The subsequent enhanced outgassing is the cause of the larger nongravitational forces.

INTRODUCTION

The Oort effect [Oort 1950] is the tendency for near-parabolic comet energies to cluster in a narrow, bound, range of values. When corrected for planetary perturbations, long-period (> 200 yr) comets have ≈ 25% of their energies occurring in the upper 0.2% of the bound range. An additional 10% are found to be unbound. The energy distribution of comets whose orbit determinations have been designated as highest quality (class I) [Marsden 1989] is shown in Fig. 1. These results are in reasonable agreement with the idea that the detected Oort cloud is the external region of a contiguous comet distribution made observable by the actions of the Galactic tidal torque [Heisler and Tremaine 1986; Duncan, Quinn and Tremaine 1987; Matese and Whitman 1989]. The tidal torque is capable of explaining that part of the observed distribution in the range $5 \leq 1/a \leq 50$ (in units of 10^{-6} AU^{-1}). In contrast, energies $1/a \leq 0$ (and $1/a \geq 50$) require an alternative explanation. Matese *et al.* [1991] have discussed those comets which have been determined to be hyperbolic originally. The question of interest is "Are these comets truly hyperbolic in origen or, if not, what is the explanation for the erroneous hyperbolic designation?"

POSSIBLE INTERPRETATIONS

- *Hyperbolic designations are due to measurement error.*

In Table 1 we list those comets for which the osculating value of 1/a is hyperbolic at a level $\geq 5\times$ the formal measured error, δ. Marsden *et al.* [1978] have noted that the true measured error may be as much as $3\times$ the formal value. Therefore multiples ≤ 5 may not be significant indicators of hyperbolic orbits. Matese *et al.* [1991] demonstrated that attributing unbound

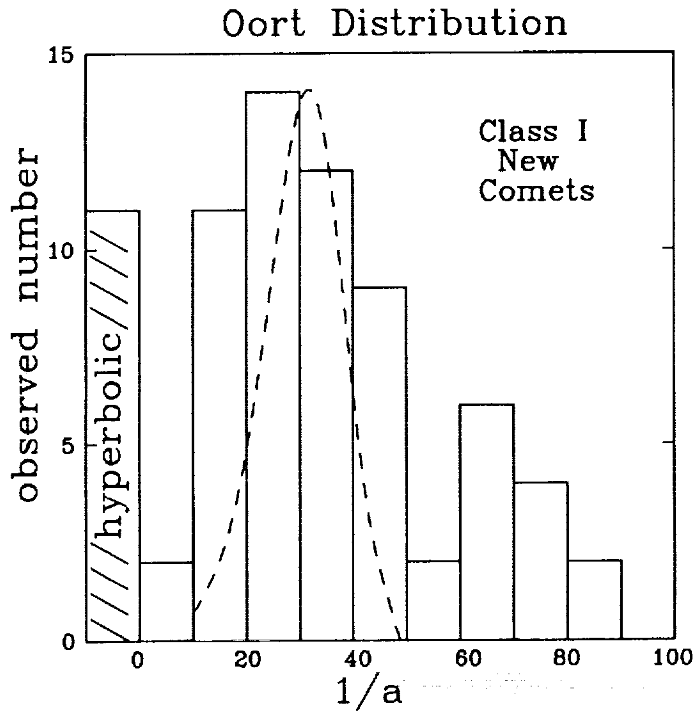

FIG. 1. The observed distribution in reciprocal semimajor axis (units= 10^{-6} AU^{-1}) of new class I comets. Also shown as a dashed curve is the Galactic tidal theory prediction in arbitrary units.

designations to measurement error can be rejected at a confidence level $\geq 95\%$ when "t" and "F" statistics are considered. This conclusion holds for both class I and class II comets.

- *Measurement errors for hyperbolic comets are badly underestimated.*

Although true measurement errors $\leq 3\times$ formal values cannot provide an explanation, the results shown in Table 1 could be attributed to errors if formal values were underestimated by factors ≥ 10 for small-q retrograde comets. However, there is no reason to expect that this is the case [Marsden, personal communication].

- *The injection mechanism for these comets is distinct from the tidal torque.*

One observes that the clearly hyperbolic comets have two distinguishing correlations; they all have small perihelia and they all move in a retrograde sense relative to the Solar system planets. Injection from the outer Oort cloud by passing stars or other distant impulses cannot explain the small-q preponderance. Nor can the correlations be explained if the comets were interstellar in origen.

- *These comets are not truly hyperbolic originally but only appear to be because of the neglect of nongravitational forces due to outgassing, flaring or splitting.*

This has previously been suggested [Marsden and Sekanina 1978] and is supported by the fact that six of the seven comets listed in Table 1 have been noted to have physically split or to have their orbit residuals significantly reduced by the inclusion of modeled nongravitational forces. The suggestion is consistent with the small-q correlation but requires an explanation for the correlation with retrograde orbits. Matese *et al.* [1991] have demonstrated that small-q prograde comets exhibit *no* comparable hyperbolic tendency.

Table 1. Comets That are Most Confidently Hyperbolic

Class	Name	1/a	±	δ	cos i	q	Comment
I	1895 IV	-172	±	8	-0.784	0.192	a
I	1953 II	-125	±	9	-0.125	0.778	c
I	1899 I	-109	±	9	-0.832	0.327	a
I	1957 III	-98	±	6	-0.498	0.316	b
II	1955 V	-727	±	121	-0.301	0.885	a
II	1989 XIX	-218	±	34	-0.003	0.642	b
II	1960 II	-135	±	23	-0.937	0.504	b

a. known to have split
b. residuals improved by modeling nongravitational forces
c. inconclusive improvement in residuals from modeling

COLLISIONAL SURFACE PROCESSING

We now argue that the distinction between small-q prograde and retrograde Oort cloud comet energies occurs because in the latter case comet mantle processing will be increased due to more energetic collisions with ecliptic plane material. In essence, impacts on small-q comets are most important for their catalytic role in the creation of large nongravitational forces. It has neen noted that neglecting nongravitational forces will induce a systematic error in the estimate of the original energy causing it to appear more hyperbolic [Marsden *et al.* 1978].

Marsden and Sekanina (1971) have suggested that physical splitting and erratic behavior of coreless short-period comets could be attributed to the single impacts of an ecliptic plane population of objects of mass $\sim 10^8$ g if their spatial density was $\sim 2\times10^{-18}$ g cm^{-3}. Such densities are $\sim 10^4\times$ larger than is known to exist in the vicinity of the earth. We suggest instead that at sufficiently high relative velocities the known meteoroidal population can indirectly expose a significant fraction of the volatiles underlying a cometary mantle.

The relative velocity between a near-parabolic comet and material in a circular ecliptic-plane orbit of radius r is

$$U(r) = \frac{V_\oplus}{\sqrt{r(\mathrm{AU})}}\sqrt{3 - \sqrt{\frac{8q}{r}}\cos i} \ .$$

One observes that at $r \approx q$ relative velocities in the range 50–150 km s^{-1} occur for the comets listed in Table 1. Following Marsden and Sekanina [1971], the meteoroidal mass required to create a crater of diameter d_o in loose mantle material is

$$m = 4\times10^{-7} d_o^3(\mathrm{cm})\left(\frac{U}{100\ \mathrm{km\ s^{-1}}}\right)^{-2} \mathrm{g}.$$

The local meteoroidal distribution peaks at a mass $\sim 10^{-5}$g [Grün *et al.* 1985]. Therefore the bulk of the meteoroidal mass distribution is capable of exposing the underlying volatiles in mantles of thickness $h \sim d_o \leq 3$cm if the impact velocity is comparable to that obtained for the retrograde small-q hyperbolic comets that are listed in Table 1.

The impact flux (energy/area/time) on a comet surface due to meteoroids is $\frac{1}{8}\rho_m U^3$ where ρ_m is the spatial mass density of all objects $\geq m$. Leinert *et al.* [1983] adopted a spatial distribution $\propto r^{-1.3}\exp(-2.1|z/r|)$, 0.1AU$\leq r \leq$ 3AU. We have integrated the orbits to estimate the impact energy per unit area inside 1 AU. For the four class I comets that are listed in Table 1 the estimated values are $(1.6, 0.04, 0.9, 0.5)\times10^5$ erg cm^{-2}. At values $\sim 10^5$ erg cm^{-2} we see that a typical meteoroid of 10^{-5}g at a speed $\sim$100 km s^{-1} will yield $\sim$ one 3 cm diameter crater per m^2 of comet surface. Thus $\leq$ one part in 10^3 of the underlying volatile surface can be expected to be directly exposed (if the mantle thickness $h \leq 3$ cm). Activity from such a small fraction of the surface cannot, in itself, cause a large nongravitational force.

The nature of comet mantles is insufficiently understood to allow a definitive analysis of the growth (or healing) of impact-produced volatile crater areas. However a dimensional argument suggests that *if* a crater of initial diameter $d_o \approx h$ does grow to diameter $d \gg h$, the linear growth time scale will be $\tau \sim \rho_{mantle} d/\bar{\phi}$ where $\bar{\phi}$ is the time averaged mass flux from the outgassing crater. For small-q, crater growth to $d \approx$ 100cm is suggested over time scales on the order of days since ϕ is an extremely sensitive function of r. We emphasize that a number of small craters would have their net area grow faster than a single crater with the same initial area. Marsden [1989] has listed 17 class I new comets whose perihelia are inside 1 AU. Of this number 8 are retrograde and half of these are clearly hyperbolic . We infer that the probability that a retrograde small-q Oort cloud comet will have its surface processed sufficiently to induce detectable nongravitational effects is $\approx \frac{1}{2}$ while that of a prograde small-q comet is $< \frac{1}{9}$.

The authors would like to acknowledge the support of a NASA/Ames University Consortium Grant and a grant from the Louisiana Education Quality Support Fund.

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