COSMIC ROULETTE: COMETS IN THE MAIN BELT ASTEROID REGION

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Abstract. We have produced top ten ranked lists of impact velocity, main belt asteroid region dwell times and impact probabilities for a selection of short period comets. The comet with the combined highest ranking with respect to impact probability and impact velocity is Comet C/1766 G1 Helfenzrieder. Since it is not clear that this comet still exists, the highest ranked, presently active, comet with respect to the likelihood of suffering impacts from meter-sized objects while in the main belt asteroid region is Comet 28P/Neujmin 1. We find no evidence to support the existence of a distinctive sub-set of the short period comets liable to show repeated outburst or splitting behaviours due to small body, meter-sized, asteroid impacts.

Keywords: Asteroid impacts, Comet 28P/Neujmin 1, cometary nuclei, cometary outbursts

1. Introduction

When a comet with a low inclination orbit moves through the region between ∼2 to ∼4 AU from the Sun it is liable to suffer collisions with particles moving in the main belt asteroid region. The probability of a collision occurring will depend upon the size of the cometary nucleus, the size of the impactor and the comet's orbital characteristics. The likelihood of an impact will further depend upon the dwell-time (T_{Dwell}) of the comet in the main belt region – this quantity is also dependent upon the comets orbital characteristics. The consequences of an impact upon a comet will, it is presumed, depend upon the size of the impactor and the impact velocity.

While it has long been clear that impacts on cometary nuclei must occur at some level (Fernandez, 1981; Harwit, 1969) there is presently no clear consensus on what the consequence of such impacts might be. Also, it is not clear whether we should expect to see impact related phenomena and be able to distinguish them from other kinds of cometary outburst generation mechanisms (Hughes, 1990). This being said, the recent outburst of transitional object 133P/Elst-Pizarro (minor planet 7968) has been interpreted by Toth (2000) as being the result of a collision with debris from asteroid 427 Galene. Presumably large impactors have a greater effect (e.g., through crater excavation) than smaller ones for a given impact velocity. While the more frequent smaller impacts may result in considerable surface compaction and "gardening" (Williams et al., 1993), it is to be expected that large

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body impacts will result in the exposure of extensive new areas of fresh surface ices. Perhaps the best candidate for an impact related outburst is that of Comet 1P/Halley observed in early 1991. The outburst occurred when the comet was some 14.3 AU from the Sun and, as suggested by Hughes (1991), was probably due to a collision with a meter-sized asteroid. The kinetic energy released in a collision with comet 1P/Halley will be high (even for relatively small impactors) because of the retrograde motion of the comet. At a heliocentric distance of 14.3 AU the collision velocity with 1P/Halley was of order 12 km/s – assuming the impactor moved on a circular orbit. The energy required to "power" the 1991, 1P/Halley outburst was some $10^{14\pm2}$ Joules (Hughes, 1991). Comparable amounts of energy to that released during the 1P/Halley outburst can be generated during collisions between meter-sized main belt asteroids and short period comets. We might naively expect, therefore, to see a distinct collision generated outburst signature within the short period, Jupiter family, comets. This being said, we note that Pittich (1971) has observed that the distribution of cometary outbursts and splitting events are not concentrated towards the ecliptic and/or the main belt asteroid region. None-the-less, some comets because of their specific orbit and size are predisposed towards suffering impacts while they move through the main belt region, and it is these that we wish to investigate.

In the sections that follow we set out to identify which of the presently known short-period comets (periods less than 20 years) are most at risk with respect to collisions from small, meter-sized asteroids while they traverse the main belt asteroid region. We shall rank the comets according to greatest impact velocity, dwell-time in the main belt region and impact probability.

2. Impact Probabilities and Ranking

A number of factors will influence the likelihood of a comet being struck while passing through the main belt region of the asteroid belt. In addition to the actual time spent in the main belt region (T_{Dwell}) there is also the intrinsic probability of being hit (P_i). Wetherill (1967) has described how intrinsic probabilities are calculated, but they essentially quantify the combined impact probabilities of all possible comet-asteroid pairings. In addition the actual probability of a hit will depend upon the size (R_C) of the cometary nucleus.

The dwell time can be calculated from Kepler's equation, $n(t - t_0) = E - e\sin(E)$ where "n" is the mean anomaly ($2\pi/T$, where T is the orbital period), "t" is the time since perihelion (t_0), E is the eccentric anomaly in radians and "e" is the orbital eccentricity. We can calculate the eccentric anomalies at the time that the comet enters (E_i) and leaves (E_o) the main belt region by ascribing heliocentric distance to the inner (D_i) and outer (D_o) regions of the main belt region. In this way, for example, $e\cos(E_i) = 1 - D_i/(a\cos(\mathrm{inc}))$, where "$a$" is the orbital semi-major axis of the comet and where "inc" is the comet's orbital inclination. The

E_o term is calculated in a similar manner. Once the eccentric anomalies have been determined the time interval between entering and leaving the main belt region can be calculated through two applications of Kepler's equation. We have chosen $D_i = 2.06$ AU and $D_o = 3.65$ AU for our set of calculations.

Constant dwell time boundaries can be placed in the (a-e) plane in a straightforward manner, for example, comets with perihelia $q > D_o$ and aphelia $Q < D_i$ will not enter the main belt region and consequently they will have $T_{\mathrm{Dwell}} = 0$. The two zero dwell time boundaries are shown in Figure 1. Also shown in Figure 1 are the loci corresponding to (a, e) values for $q = 2.06$ AU and $Q = 3.65$ AU. The circles shown in Figure 1 correspond to the orbital (a, e) values of the comet set (see later) that is to be ranked.

An approximate formula for the velocity with which an asteroid, moving along a circular orbit, will hit a comet with orbital elements (a, e, inc) has been determined by Opik (1951). We show in Figure 2, for illustrative purposes, contours of impact velocity with asteroids at the inner boundary of the main belt when inc = 0°. For a comet with $a = 4.0$ AU, the impact velocity will range from a few km/s when $e \sim 0.5$, to some fifteen km/s when $e \sim 0.8$. As the inclination increases so too does the impact velocity for a given combination of (a, e). The average (a, e, inc) values for our cometary set are (3.98, 0.54, 12.34) and consequently the typical velocity with which a short period comet might be impacted is of order 9 km/s. For a 1-meter diameter impactor the typical impact energy will be of order 10^{11} Joules. This "typical" impact energy is of order that reported for cometary outbursts in general (Hughes, 1990; Gronkowski and Smela, 1998).

The probability of a comet of radius R_C being struck by an impactor of size $r_{\min}$ is determined according to the integral relation

$$P = \int_{r_{\min}}^{r_{\max}} \frac{\mathrm{d}N}{\mathrm{d}r} (R_C + r)^2 P_i \, \mathrm{d}r,$$

where dN is the number of impactors in the size range from r to $r + \mathrm{d}r$ within the main belt asteroid region, P_i is the intrinsic probability, and $r_{\max}$ is the upper size limit of objects under consideration. Bottke et al. (1995) find that for $r \leq r_{\max} = 85$-m, $\mathrm{d}N/\mathrm{d}r = 8.3 \times 10^2/r^{3.5}$. Once the intrinsic probability has been determined for a given cometary orbit, the impact probability against collisions with objects of size $r_{\min}$ can be calculated provided R_C is known. Intrinsic probabilities and average impact velocities for short period comets with periods less than 20 years have been calculated by Gil-Hutton (2000), and we use his list of comets for our rankings given in Table I. Gil-Hutton's list contains the orbital parameters (a, e, inc) for 159 objects amongst which are periodic comets seen more than once, comets with derived short periods but seen only once, as well as short period comets that have now become lost and/or destroyed. The list also includes apparently transitional, that is intermittently active comets such as 107P/Wilson-Harrington (minor planet 4015 1979 VA) and 72P/Denning-Fujikawa (see Beech, 2001).

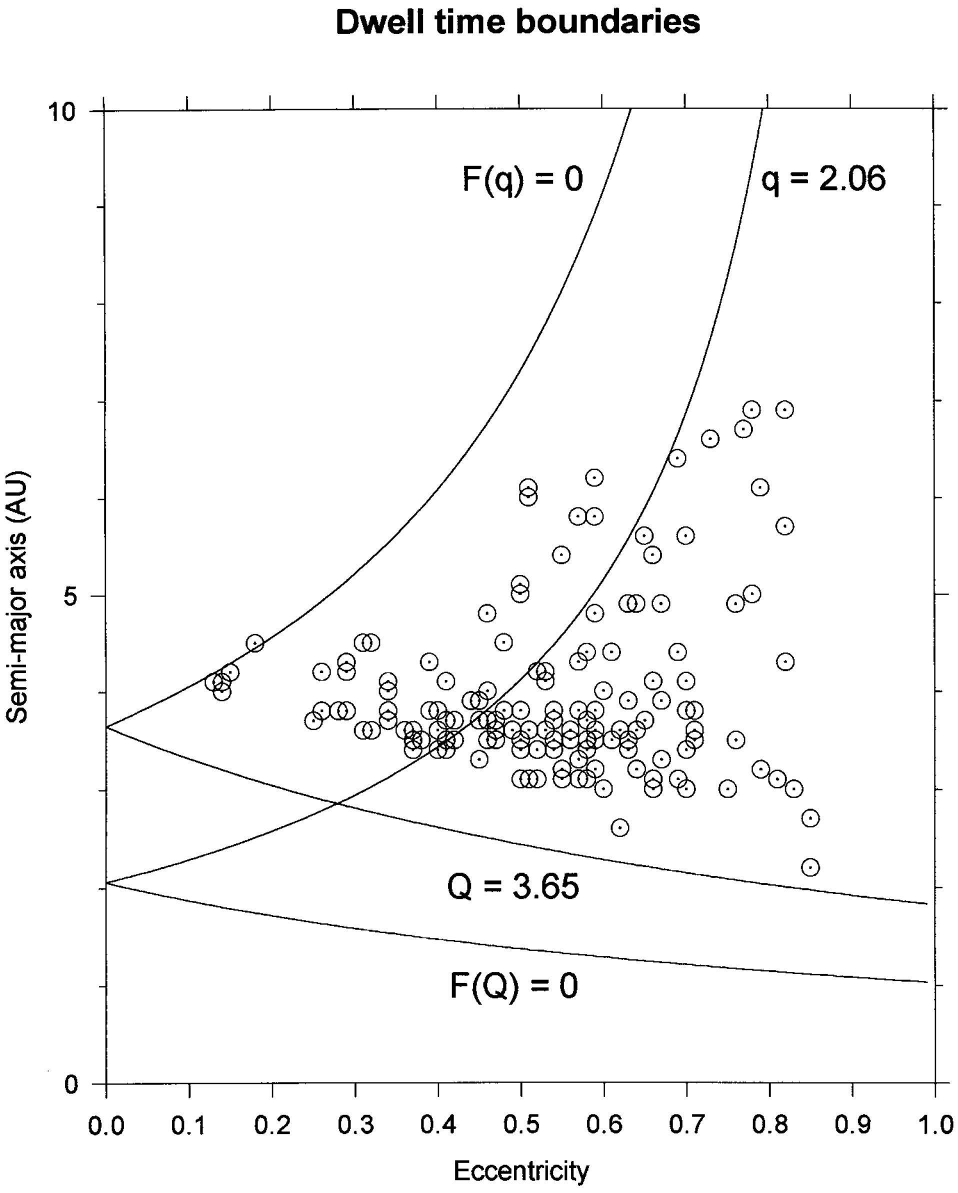

Figure 1. Zero dwell-time boundaries. Comets with orbital (a, e) in the region above the boundary labeled $F(q) = 0$ have perihelia greater than the chosen outer boundary of the asteroid belt ($D_o = 3.65$ AU). Comets with orbital (a, e) below the line labeled $F(Q) = 0$ have aphelia smaller than the inner boundary of the asteroid belt ($D_i = 2.06$ AU). The locus labeled $q = 2.06$ separates out those comets with perihelia less than $D_i = 2.06$ AU. The locus labeled $Q = 3.65$ separates out those comets with aphelia less than $D_o = 3.65$ AU. The open circles indicate the (a, e) combinations for the cometary data set under consideration.

TABLE I

Comparison of top 10 ranked comets. Numbers in brackets refer to the actual quantity being ranked in descending order. Column one is the ranked average impact velocity as calculated by Gil-Hutton (2000); column two is the ranked dwell time in years; column three is the ranked dwell time per orbit; the last two columns are impact probabilities for $r_{\min} = 0.5$-m – see notes a and b and text for details

Velocity (km/s)	T_{Dwell} (yr)	T_{Dwell}/period (%)	Prob. Per orbit (%)[a]	Prob. Per orbit (%)[b]
96P/Machholz 1 (M) (23.83)	149P/Mueller 4 (2.13)	127P/Holt–Olmstead (59.27)	C/Helfenzrieder (L) (2.04)	103P/Hartley 2 (0.052)
8P/Tuttle (M) (22.59)	14P/Wolf (M) (2.07)	77P/Longmore (57.70)	28P/Neujmin 1 (1.73)	D/Lexell (L) (0.034)
126P/IRAS (18.98)	77P/Longmore (2.05)	86P/Wild 3 (54.41)	39P/Oterma (1.58)3	Lovas 2 (R) (0.032)
5D/Brorsen (L) (18.07)	Shoemaker 4 (R) (2.01)	105P/Singer–Brewster (54.20)	103P/Hartley 2 (0.76)	107P/Wilson–Harrington (0.032)
McNaught–Russell (R) (18.00)	101P/Chernykh (S) (1.97)	94P/Russell 4 (54.05)	10P/Tempel 2 (0.60)	87P/Bus (0.031)
72P/Denning–Fujikawa (17.55)	134/Kowal–Vavrova (1.95)	48P/Johnson (53.58)	74P/Smirnova–Chernykh (0.55)	143P/Kowal–Mrkos (0.031)
C/Helfenzrieder (L) (17.23)	33P/Daniel (1.95)	87P/Bus (53.51)	65P/Gunn (0.52)	116P/Wild 4 (0.031)
45P/H–M–P (17.05)	17P/Holmes (1.89)	110P/Hartley 3 (53.50)	D/Skiff–Kosai (L) (0.51)	57P/DT–N–D (0.031)
Pigott (L) (16.84)	53P/Van Briesbroeck (1.88)	17P/Holmes (53.28)	D/Tritton (L) (0.50)	140P/Bowell–Skiff (0.031)
21P/Giacobini–Zinner (M) (16.61)	83P/Russell 1 (1.86)	65P/Gunn (52.92)	116P/Wild 4 (0.38)	31P/S–W 2 (0.030)

Abbreviation key: (R) Awaiting second return; (L) lost; (S) split; (M) associated meteor shower; H–M–P = Comet Honda–Mrkos–Pajdusakova; S–W 2 = Comet Schwassmann–Wachmann 2; DT–N–D = Comet Du Toit–Neujmin–Delporte.

[a] Probability per orbit according to deduced radii – see text for discussion and Table II. Calculated for an impactor size $r_{\min} = 0.5$ m.

[b] These are comparative impact probabilities per orbit, calculated upon the basis that all the comets have the same sized nucleus ($R_C = 1$ km). This column essentially picks out those comets that have high impact probabilities because of their orbital characteristics (as expressed through the Pi term) rather than because of their physical size. Calculated for an impactor size $r_{\min} = 0.5$ m.

[c] As a result of a close jovian encounter in 1963, comet 39P/Oterma no longer passes through the main belt asteroid region.

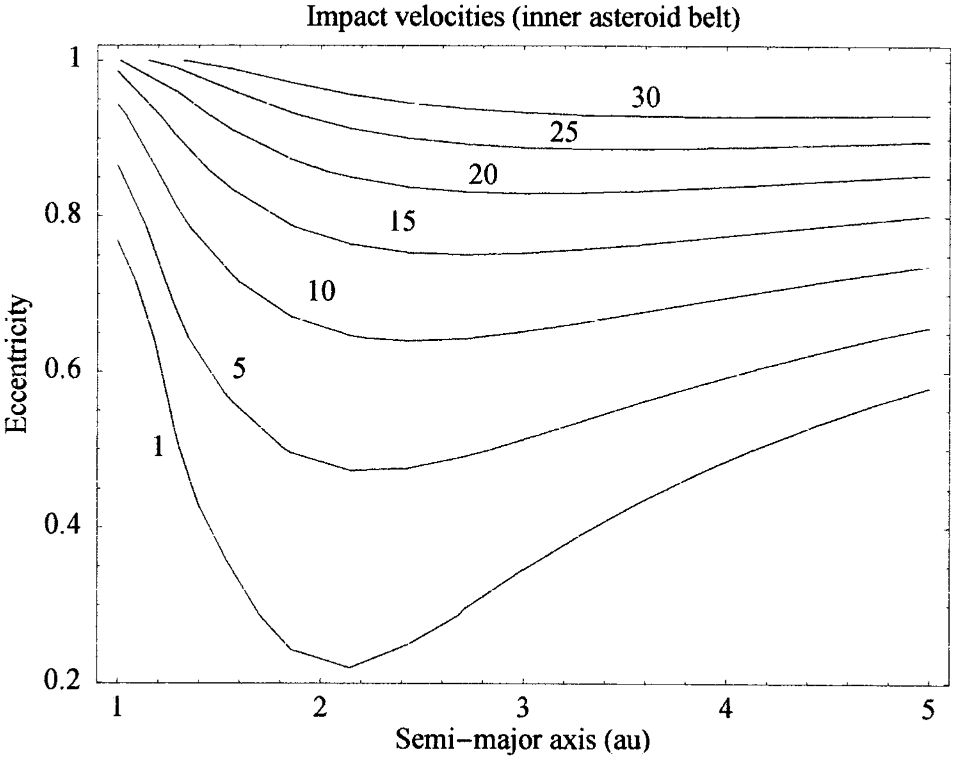

Figure 2. Impact velocities for various (a, e) combinations. The collision velocities correspond to those of a comet with a given (a, e, inc = 0°) and an asteroid moving along a circular orbit at the inner edge of the main belt region (a = 2.06 AU). The contours are labeled according to collision velocity in km/s. Comets with orbital inclinations greater than zero will have impact velocities larger than those shown in the figure.

Before the impact probability P can be evaluated an estimate of R_C is required for each comet listed in Gil-Hutton (2000). Only a very few comets have well determined radii (and we discuss some of these below). In an attempt to be at least consistent we have used in our calculations the nuclear radii listed in the *Catalog of Nuclear Magnitudes of Jupiter Family Comets* by Tancredi et al. (2000). The radii given in this catalog have been derived in a consistent manner and are based upon an assumed geometric albedo of four percent. For those comets not listed in Tancredi et al. (2000) we have used the formula of Hughes (1987) which relates the size of a comet to its absolute magnitude H_{10} via the relation: $\mathrm{Log}_{10}[R_C(\mathrm{km})] = 1.842 - 0.2H_{10}$. Absolute magnitudes have been taken from Kresak and Kresakova (1989) and from the *Notes Cometaires du Bureau des Longitude*, Paris (www.bdl.fr/ephem/comets/HTML/francais/Trinium.html). This latter method of estimating cometary radii is the least satisfactory in that a comets brightness is a complex function of its gas and dust production rate, the fraction of the nucleus that is undergoing active sublimation and the actual albedo of cometary surface material. We proceed on the basis that, in most cases, the sizes of cometary nuclei are not well known, but are, if nothing else reasonably well constrained.

3. Discussion of Cometary Rankings

We have calculated top ten ranked lists of comets according to average impact velocity (as given by Gil-Hutton, 2000), dwell time in years, dwell time per orbit, probability of impact per orbit, and the probability of impact per orbit if $R_C = 1$ km. The resultant rankings, given in Table I, provide an interesting assembly of comets. No one comet, however, ranks highly in all five categories. This is essentially a result of orbital "characteristic" sorting. The high impact velocity comets are those with high orbital inclinations, while the high dwell time per orbit comets are those comets with small orbital eccentricities. The high impact probability per orbit comets are essentially those with the largest deduced radii. While these orbital and nucleus selection effects do influence the strict ranking procedure employed, many of the comets listed in Table I are, none-the-less, remarkable for their apparent activity and associated histories.

The comet with the greatest dwell time in the main belt asteroid region is 149P/Mueller 4. The radius estimate for this comet is rather uncertain, and for an absolute magnitude of $H_{10} = 12.6$ we find a radius of $R_C = 0.2$ km. The impact probability against 1-m sized asteroids for this comet amounts to 0.05% per orbit. Comet 127P/Holt–Olmstead has the greatest main belt region dwell time per orbit, amounting to some 59% of its orbital period. This comet, again, has an uncertain radius and for an absolute magnitude of $H_{10} = 14.2$, we find a radius of just 0.1 km, and an impact probability of 0.01% per orbit. So, while these two comets appear to have orbits that prime them towards suffering impacts, their apparent small size mitigates against the likelihood of any impacts by large meter-sized objects.

Comets 45P/Honda–Mrkos–Pajdusakova (8th in the impact velocity ranking), 10P/Tempel 2 (6th in the impact probability per orbit ranking) and 65P/Gunn (8th in the impact probability per orbit ranking) are associated with large meteoroid dust tails (Sykes and Walker, 1992) and these are possibly impact produced debris trails. Comet 101P/Chernykh (5th in dwell time ranking) was observed to split in 1991, and comet 53P/Van Briesbroeck (9th in dwell time ranking) is believed twined with comet 42P/Neujmin 3, the pair having split apart circa 1850 (Carusi et al., 1985). Whipple (1984, 1999) has suggested that comet 17P/Holmes (7th in dwell time and 8th in dwell time per orbit ranking) was a double nucleus comet, with its 1892 and 1893 outbursts being related to the merger and accretion of one nucleus by the other. Among the erratic comets known to have experienced major orbital anomalies (Sekanina, 1993) are comets 5D/Brorsen (4th in the impact velocity ranking) and 31P/Schwassmann–Wachmann 2 (9th in the comparative impact probability ranking). Likewise, among Kresak's (1987) list of intermittently active comets we find comet 5D/Brorsen (again), 45P/Honda–Mrkos–Pajdusakova

TABLE II

Adopted cometary radii for impact probability calculations (see column 4 of Table I). Column one identifies the comet, column two gives the adopted radius and column three indicates the data source. The highest ranked comet in our impact probability list is comet C/1766 G1 Helfenzrieder. This result is highly uncertain, however, since the comet has not been well observed. Estimates of its absolute magnitude have been taken from the list given by Kronk (1999), and its radius is poorly constrained. The comet has number one ranking if $H_{10} = 4.5$, it drops to 7th ranked if $H_{10} = 6.0$ and 17th ranked if $H_{10} = 6.8$. The radius for comet 28P/Neujmin 1 is well constrained by the observations (see Rahe et al., 1994), and we can be reasonably certain that its high ranking in the impact probability list is correct. Likewise comet 10P/Tempel 2 has a radius that has been reasonably well constrained by several sets of independent observations (Rahe et al., 1994)

Comet	Radius (km)	Comments
C/Helfenzrieder	8.7 / 4.4 / 3.0	Hughes (1987); $H_{10} = 4.5 / 6.0 / 6.8$
28P/Neujmin 1	10.4	Rahe et al. (1994)
39P/Oterma	9.1	Tancredi et al. (2000)
103P/Hartley 2	3.8	Tancredi et al. (2000)
10P/Tempel 2	5.6	Rahe et al. (1994)
74P/Smirnova–Chernykh	6.0	Tancredi et al. (2000)
65P/Gunn	4.8	Tancredi et al. (2000)
D/Skiff–Kosai	4.6	Tancredi et al. (2000)
D/Tritton	6.3	Tancredi et al. (2000)
116P/Wild 4	3.5	Tancredi et al. (2000)

(again) and comet 72P/Denning–Fujikawa (6th in impact velocity ranking). The on-again, off-again activity of these comets may possibly be related to impact events. Beech (2001) has suggested that comet 72P/Denning–Fujikawa is an old comet evolving towards a mostly dormant state. In this sense it may be similar to Comet 107P/Wilson–Harrington (4th in the comparative probability/orbit ranking), which has an asteroid-like appearance, but is capable of occasional cometary activity. While the activity of 72P/Denning–Fujikawa and that of 107P/Wilson–Harrington may be impact modulated, the exact form of the modulation process remains unclear since the most likely impactors (per orbit) for these comets are centimeter-sized objects.

Column 4 of Table I shows the top ten ranked comets according to impact probability (with a 1-m diameter object) per orbit. The impact probability is dependent upon the adopted nuclear radius and, as mentioned above, these are not always known to any great accuracy. The radii used in our calculations are given in Table II.

Of the comets listed in column 4 of Table I, both D/1977 C1 Skiff–Kosai and D/1978 C2 Tritton are considered to be lost. Comet 39P/Oterma suffered a close jovian encounter in 1963 and upon acquiring a new perihelion distance of 5.47 AU it no longer shows any distinctive cometary activity. Of recent note, however, several research groups recently recovered the comet as a point source (IAUC 7689, 2001 August 24), a result that testifies to the large size of its nucleus. Comet 10P/Tempel 2 (6th ranked) suffered a pre-perihelion outburst shortly after passing through the main belt asteroid region in 1962 (Pittich, 1971). Campins et al. (1990) also found that comet 10P/Tempel 2 has a dust trail that is rich in large (that is millimeter to centimeter sized) “dust” grains, but as to whether these grains are impact related debris or a “feature” of the comet’s material make-up and sublimation characteristics is unclear.

The comet that ranks highest in both impact velocity (7th ranked) and impact probability per orbit (1st ranked) is comet C/1766 G1 Helfenzrieder. This comet has not been recovered since its initial discovery in April of 1766. Numerical calculations performed by Carusi et al. (1985) indicate that the orbit of comet Helfenzrieder varies in a somewhat erratic manner, due to numerous close encounters with the Jupiter. The perihelion and aphelion distances of the comet, however, have hardly changed since the early 1600s. On the basis that its orbital period has remained nearly constant since 1766, comet Helfenzrieder has apparently been inactive during its last 50 perihelion passages. If comet Helfenzrieder still exists, and it may well not (Kresak and Kresakova, 1989), it possibly requires a substantive impact to re-initiate further cometary activity. We note from Table I that our impact probability per orbit calculation suggests that comet Helfenzrieder will encounter a meter-sized impactor every 50 orbits or so. Note, however, that this probability is evaluated for a radius of 8.7 km, which is based upon an uncertain absolute magnitude $H_{10} = 4.5$ – see Table II. The impact energy of a 1-m diameter asteroid of density 3000 kg/m^3 with comet Helfenzrieder will be of order 5×10^{11} Joules (the average impact velocity is taken from Gil-Hutton, 2000, as 17.23 km/s). This amount of impact energy is comparable to that associated with the outburst of comet 1P/Halley in 1991 (Hughes, 1991). The radius of comet 28P/Neujmin 1 (2nd ranked in impact probability), unlike comet Helfenzrieder, is well constrained at $R_C = 10.4$ km (Rahe et al., 1994), and it too has a high average impact velocity of some 14.67 km/s. Comet 28P/Neujmin 1 has an orbital period of some 18.1 years, so the time interval between possible impacts with meter sized objects will be of order 10^3 years.

Column 5 in Table I is a ranked list of impact probabilities for one-meter sized objects under the assumption that all cometary nuclei are of the same size ($R_C = $ 1-km). This column distinguishes those comets that have high intrinsic impact probabilities (P_i) because of their orbital characteristics. Of the comets listed in column 5, both Lexell, and Lovas 2 are considered lost. Comet 57P/du Toit–Neujmin–Delporte (8th ranked) underwent an apparent outburst at the time of its discovery in July 1941 (Pittich, 1971) when it was some 1.31 AU from Sun, and having just passed through the inner edge of the main belt asteroid region.

Comets 96P/Machholz 1 (1st in impact velocity ranking), 8P/Tuttle (2nd in impact velocity ranking) and 14P/Wolf (2nd in dwell time ranking) are all associated with active annual meteor showers; these are the Quadrantids, Ursids, α-Capricornids respectively. Comet 21P/Giacobini–Zinner (10th in impact velocity ranking), which has shown outburst activity during its 1946 and 1959 perihelion returns (Pittich, 1971) is associated with the intermittently active Draconid meteor shower. There is no obvious association between meteor shower activity and collisions, but presumably collisions might place large meteoroids into a cometary stream. This being said, neither the Ursids nor the Quadrantids are known for their fireball producing capabilities. Comet 14P/Wolf, on the other hand, may be the parent to a sibling comet, comet D/1892 T1 Barnard 3 (Neslusan, 1999), and the α-Capricornid shower is noted for its occasional delivery of bright fireballs.

In conclusion, while many of the comets listed in Table I show, or have shown, activity that is consistent with an impact origin, there appears to be no distinct group of comets that have high impact probabilities, high impact velocities and long dwell times in the main belt asteroid region. While impacts upon cometary nuclei must happen, there is presently no clear-cut impact signature to be distinguished in the observable behaviours of any sub-set of the short-period, Jupiter family comets. Of the presently known to be active comets with well-constrained radii, it is comets 28P/Neujmin 1 and 10P/Tempel 2 that are most likely to suffer impacts while passing through the main belt asteroid region.

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