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Comet 72P/Denning–Fujikawa: down but not necessarily out

Martin Beech★
Campion College, The University of Regina, Regina, SK, Canada S4S 0A2

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ABSTRACT

It is argued that Comet 72P/Denning–Fujikawa is an old and intermittently active comet evolving, at least observationally, towards a transitional minor planet status. We have studied the fate of hypothetical meteoroids ejected from the comet during its two known periods of activity (1881 and 1978). A complex history of orbital evolution is found. Meteoroids ejected in 1881 first become Earth-orbit-crossing in 1960, while meteoroids ejected in 1978 appear to hold stable, non-Earth-orbit-crossing orbits until at least 2110. If copious amounts of meteoroids were ejected in 1881 we find some indication that the Earth may encounter a populous, coherent subgroup, or 'streamlet', of them in 2009 and 2010, leading to the possibility of outburst activity in those years. We have investigated the possibility that the activity of Comet 72P/Denning–Fujikawa, over the past ~200 years, has been governed by impacts suffered by the comet as it moves through the main-belt asteroid region. While encounters with centimetre-sized objects will take place each time the comet orbits the Sun, the likelihood of the comet encountering a large metre-sized asteroid is essentially zero on the time-scales considered. The outburst activity of the comet may be impact-modulated in the sense that small-object impacts might trigger the explosive release of gases trapped in subsurface cavities.

Key words: comets: individual: 72P/Denning–Fujikawa – meteors, meteoroids – minor planets, asteroids.

1 INTRODUCTION

Out of its last 14 perihelion passages, Comet 72P/Denning–Fujikawa has been recovered just twice. The first recovery, and indeed discovery, of the comet (designation 1881 T1) was on 1881 October 4, when W. F. Denning detected it as a small centrally condensed 'nebula' in Leo (Denning 1881a; Vsekhsvyatskij 1964). Its second recovery was by Shigehisa Fujikawa on 1978 October 9 (designation 1978 T2). Denning recovered the comet as a post-perihelion passage, 8th-magnitude object, while Fujikawa found it as an 11th-magnitude, post-perihelion object (Marsden 1978).

Numerical integration of the orbital parameters for Comet 72P/Denning–Fujikawa indicates that, while it periodically passes close to Jupiter, it has held a remarkably stable orbit since at least the late 16th century (Carusi et al. 1985; see also data at http://ssd.jpl.nasa.gov/horizons.html). Table 1 shows the orbital elements derived for the comet in 1881 and 1978. Using the numerical integration data and deduced absolute magnitude of the comet (see last column in Table 1), Kresak (1991) has noted that Comet 72P/Denning–Fujikawa made very favourable approaches to the Earth in 1829 (i.e. before its discovery in 1881), 1960 and 1969. At these times the comet should have been brighter than magnitude 8.0, and, indeed, in 1829 the comet should have been a magnitude 5 object. Table 2 shows the Earth-encounter conditions for each perihelion passage of Comet 72P/Denning–Fujikawa since 1881. In addition to the years highlighted by Kresak (1991), we note that it is also somewhat surprising that the comet was not recovered (post- or pre-perihelion) during its 1916, 1987 and 1996 returns, and especially so in the last two returns since the comet was actively anticipated. The combined observations and orbital integrations indicate that, of the 14 perihelion passages since 1881, Comet 72P/Denning–Fujikawa has been recovered twice and 'missed' on five good to reasonable Earth-encounter occasions. It seems reasonable to conclude therefore that Comet 72P/Denning–Fujikawa was not active during its perihelion returns in 1829, 1916, 1960, 1969, 1987 and 1996. The intermittent activity of Comet 72P/Denning–Fujikawa suggests that it is a transitional comet, similar to Comet 15P/Finlay (Beech, Nikolova & Jones 1999) and Comet 107P/Wilson-Harrington (Fernandez et al. 1997). Given that Comet 72P/Denning–Fujikawa is only occasionally active, the question arises as to what processes control its activity.

In addition to having apparent bouts of dormancy, Comet 72P/Denning–Fujikawa is also one of the few short-period comets (the so-called 'silent comets' of Drummond 1981) that has a nodal point within 0.1 au of the Earth's orbit but is not the parent to any recognized annual meteor shower. In Section 2 below we

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★E-mail: martin.beech@uregina.ca

Table 1. The orbital characteristics of Comet 72P/Denning–Fujikawa during its 1881 and 1978 apparitions. Orbital data are from Marsden (1983). The absolute magnitudes H_{10} are from Kresak & Kresakova (1989).

Apparition	a (au)	eccen.	i (°)	Ω (deg.)	ω (°)	T_0	H_{10}
1881 T1	4.2327	0.8287	6.870	66.935	312.476	Sept. 13.749	8.3
1978 T2	4.3295	0.8202	8.668	40.968	334.045	Oct. 02.042	12.6

investigate this apparent lack of associated meteoric activity by considering the orbital evolution of hypothetical meteoroids ejected from Comet 72P/Denning–Fujikawa. The specific aim of Section 2 is to determine whether the meteoric 'silence' of Comet 72P/Denning–Fujikawa is because it is an inherently inactive comet, or whether it is because the orbital evolution of any ejected meteoroids is such that the production of a meteor shower is not actually favoured.

2 THE FATE OF THE 1881 AND 1978 METEOROIDS

Shortly after he discovered Comet 1881 T1, Denning (1881b) discussed the possibility that it might have an associated meteor shower. Denning made his suggestion on the basis that 1881 T1 passed closer to the Earth's orbit than any other known comet at that time (Comet 3D/Biela did technically pass closer to the Earth's orbit, but by 1881 it had been 'lost' for some 29 years: Babadzhanov et al. 1991). Based upon the time of closest approach to the Earth's orbit, Drummond (1981) and Olsson-Steel (1987) have determined that meteoroids related to Comet 72P/Denning–Fujikawa might be encountered in either August or December. The theoretical radiant point data are summarized in Table 3. Of the two possible shower dates, that in December is favoured since it is at this time that the comet makes its closest approach to the Earth's orbit. Unfortunately the December shower would be a southern hemisphere daytime event, making it accessible only to radio and radar studies. Using the D'-criterion stream-search method Olsson-Steel (1987) has found, however, that there are about a dozen meteors (out of a total of 3759 recorded during the Adelaide radar surveys conducted in 1960–61 and 1968–69) with orbits similar to that of Comet 72P/Denning–Fujikawa. Hasegawa (1990) has also calculated potential meteor shower dates for Comet 72P/Denning–Fujikawa, but his method is based upon the condition that the cometary heliocentric distance and the orbital longitude coincide with those of the Earth. He consequently predicts a night-time shower in the first week of August (see Table 3). A number of weak meteor showers are active towards the end of July and early August each year (namely the α-Capricornids, the Southern ι-Aquarids and the Northern δ-Aquarids: see e.g. Rendtel, Arlt & McBeath 1995), but none can be reasonably associated with the theoretical radiant derived for Comet 72P/Denning–Fujikawa (see Table 4). It appears that Comet 72P/Denning–Fujikawa is indeed meteorically 'silent' at the present epoch, although, as pointed out by Hughes (1990), if the delivery rate of meteoroids from a stream is less than two visible meteors per hour, then it is highly unlikely that a shower detection will be made. We also note in passing that several authours have in the past suggested an association between Comet 72P/Denning–Fujikawa and the α-Capricornids, but there seems to be no justification for such an association on the basis of the observed and the theoretical radiant position data. Neslusan (1999) has also recently argued that the α-Capricornid meteors are most likely associated with Comet 14P/Wolf.

Table 2. Comet 72P/Denning–Fujikawa encounter conditions for each perihelion passage since 1881. The geocentric elongation is given in column 2 and the distance between the Earth and the comet at perihelion, Δ(au), is given in column 3. The last column gives the estimated magnitude of the comet when at perihelion. The magnitudes are calculated according to $m(q) = 10.5 + 5\log\Delta + 10\log q$, where q is the perihelion distance.

Perihelion passage	∠(Sun–Earth–Comet) (°)	Δ(au)	$m(q)$
1881	37.2	0.4	7
1890	15.8	1.6	10
1899	10.2	1.7	10
1908	36.2	1.3	10
1916	9.3	0.3	6
1925	33.5	1.4	10
1934	19.9	1.6	10
1943	6.0	1.7	10
1952	38.1	1.2	10
1960	48.6	0.4	8
1969	40.5	0.3	7
1978	23.5	0.3	6
1987	45.3	1.0	9
1996	23.9	1.6	10

While the Adelaide radar data hint at the possibility that some Comet 72P/Denning–Fujikawa ejected meteoroids do reach Earth orbit, it is still a little surprising that no clearly observable shower is evident. In order to investigate the reasons for the apparent lack of an associated meteor shower, we have performed a series of numerical integrations that follow the orbital evolution of many thousands of hypothetical meteoroids ejected from Comet 72P/Denning–Fujikawa during its 1881 and 1978 perihelion returns. We have specifically chosen perihelion passages when the comet was known to be active, and we assume for the sake of argument that meteoroids could have been ejected anywhere along the arc constrained by the heliocentric distance, r, with $q < r(\mathrm{au}) < 2.5$, where q is the perihelion distance and where it is assumed that water ice sublimation begins once the heliocentric distance is smaller than 2.5 au. We also assume for the sake of argument that meteoroids can be ejected from the entire Sun-facing hemisphere of the cometary nucleus. In this manner, we can at least evaluate the overall fate of meteoroids that could potentially be ejected from Comet 72P/Denning–Fujikawa.

In order to determine the meteoroid ejection velocity, we first need to estimate the size of Comet 72P/Denning–Fujikawa's nucleus. Using the formula of Hughes (1987) and the absolute magnitude data of Vsekhsvyatskij (1964) for its 1881 apparition, we estimate that Comet 72P/Denning–Fujikawa has a nuclear radius of 1.0 ± 0.5 km. We note, however, that the formula derived

Table 3. Summary of theoretical radiant positions (α, δ) for Comet 72P/Denning–Fujikawa derived meteoroids. D is the distance of closest approach to the Earth's orbit in astronomical units, and 'Date' corresponds to the day of predicted shower maximum.

Apparition	α (°)	δ (°)	D (au)	Date	Reference
1881 T1	280	−35	0.039	Dec. 17	Olsson-Steel (1987)
	305	−31	0.109	Aug. 5	Olsson-Steel (1987)
	280	−36	0.04	Dec. 17	Drummond (1981)
	299.4	−15.6	0.11	Aug. 4	Hasegawa (1990)
1978 T2	271	−40	0.080	Dec. 3	Olsson-Steel (1987)
	305	−37	0.15	Aug. 9	Olsson-Steel (1987)
	272	−42	0.08	Dec. 3	Drummond (1981)
	298.7	−21.7	0.154	Aug. 7	Hasegawa (1990)

Table 4. Radiant positions of meteor showers that reach their maximum activity in late July and early August. Column 4 gives the zenithal hourly rate (ZHR) at maximum. The ZHR is a derived quantity indicating the number of meteors brighter than magnitude +6.5 that would be seen per hour if the radiant were directly overhead. Data taken from Rendtel et al. (1995).

Shower	α (°)	δ (°)	ZHR	Maximum
α-Capricornids	307	−10	4	July 30
S. ι-Aquarids	334	−15	2	August 4
N. δ-Aquarids	335	−05	4	August 8

by Hughes (1987) does not specifically apply to comets in outburst, but the implied small size of the nucleus does not seem unreasonable with respect to the observed 'behaviour' of Comet 72P/Denning–Fujikawa. Given the uncertainty in the derived nuclear radius, however, we shall consider below the orbital evolution of meteoroids ejected from nuclei of radius 0.5, 1.0 and 2.25 km. The size of the cometary nucleus enters into the calculations with respect to the evaluation of the meteoroid ejection velocity (see below). To complete our parameter set, we assume that the hypothetical meteoroids have densities of $800\,\mathrm{kg\,m^{-3}}$, and masses of 10^{-7} kg. The orbital parameters for the comet, at each of its returns to perihelion, are taken from Marsden (1983) – see also Table 1.

For a nuclear radius of 1 km, any meteoroids ejected during the 1881 perihelion return acquire initial orbits with nodal points at $\sim$0.85 and $\sim$3.1 au. Very little sign of dramatic orbital evolution is evident in the stream until a weak jovian encounter in the early 1920s causes the nodal points to shift to $\sim$0.75 and $\sim$4.75 au. The nodal distribution of 2000 hypothetical meteoroids ejected in 1881 is shown in Fig. 1 for the time interval 1935–60. The meteoroids form a coherent stream in the time interval covered, with small variations in eccentricity and semimajor axis accounting for the spread in the heliocentric distance of the nodal points and the variation in nodal crossing times. We find that after 1925 the meteoroids ejected in 1881 pass very close to Venus ($\Delta \sim 0.03$ au), and it is possible that a meteor shower might occur in the upper atmosphere of that planet (see also Beech 1998). With the shift of the descending node outwards in the mid-1920s, the stream of meteoroids is primed for an eventual close encounter with Jupiter. The fated encounter with Jupiter takes place in 1955, and as Fig. 2 reveals the stream undergoes a dramatic re-arrangement in structure. Fig. 2 indicates that long strands, or streamlets, of meteoroids with similar orbital semimajor axis, but varying eccentricities, form after the jovian encounter. It also appears that meteoroids first become Earth-orbit-crossing after 1960. With the return of the comet to perihelion in 1978, we find that the stream meteoroids ejected in 1881 are truly scattered throughout the inner Solar system. From 1960 onwards the meteoroids appear to be Earth-orbit-, Venus-orbit- and Mars-orbit-crossing. While rich meteoric activity is not predicted at the Earth, it appears that some activity should occur, but we note that it would be difficult to separate Comet 72P/Denning–Fujikawa derived meteors from those of the sporadic background. Figs 3 and 4 show the continued orbital evolution of the 1881-ejected meteoroids through to 2020. The well-defined 'hook-like' streamlet that cuts through the ecliptic (between the orbits of Mars and Venus) beginning around 1970 shows a remarkable persistency of coherence. Interestingly, we see in Fig. 4 that the Earth should sample some of the meteoroids that make up this streamlet in 2009 and 2010, suggesting that outburst activity might be possible in those years.

Nodal distribution diagrams for the 0.5- and 2.25-km cometary radii are qualitatively similar to those shown in Figs 1–4, and they are not repeated here. For each set of calculations, however, we find that long-lived 'streamlets' are formed, but note specifically that the Earth encounter conditions around 2010 are sensitive to the assumed size of the cometary nucleus and meteoroid mass. We reiterate at this point that the foregoing results are based upon the assumption that large numbers of meteoroids were actively ejected in 1881.

If any great number of meteoroids were ejected from the nucleus of Comet 72P/Denning–Fujikawa during its 1978 perihelion passage, we find that they would have entered a stable orbital distribution with nodal points near 0.85 and 7.0 au. Indeed, we find no hint of orbital evolution towards an Earth-intercept geometry for any of the hypothetical meteoroids ejected in 1978 during the time interval ending 2110. The nodal distribution of hypothetical meteoroids ejected in 1978 in the time interval 2094–2108 is shown in Fig. 5. This last figure is slightly different from the previous nodal distribution diagrams in that the nodal points for three different meteoroid masses are shown (the nuclear radius was fixed to be 1 km in these calculations, but see below). Distinctive nodal distribution differences only begin to develop around 2105. The principal difference is that the variation in orbital eccentricity, seen as a greater spread in heliocentric distances at both the ascending and descending nodes, becomes more pronounced for the lowest mass test meteoroids (the downward-pointing filled triangles in Fig. 5). These lowest mass meteoroids are the ones ejected from the cometary nucleus with the greatest velocity. Whipple's (1951) meteoroid ejection formula gives ejection velocities of 28.3, 41.5 and $60.0\,\mathrm{m\,s^{-1}}$ for the 10^{-6}-, 10^{-7}- and 10^{-8}-kg meteoroids, respectively, at 1 au for a nuclear radius of 1 km. Since Whipple's formula indicates that for a given heliocentric distance the ejection velocity will vary as $R^{0.5}m^{-0.167}$, where R is the nuclear radius and m is the meteoroid mass, the nodal point distributions shown in Fig. 5 also demonstrate the effect of varying cometary radius. In this fashion, the 10^{-8}-kg model run is equivalent to 10^{-7}-kg meteoroids being ejected from a comet of radius 2.25 km. The 10^{-6}-kg model run is equivalent to that for 10^{-7}-kg meteoroids being ejected from a comet of radius 0.5 km. Fig. 5 indicates that the model interpretations, in the broad sense described above, are not overly sensitive to the size of the nucleus of Comet 72P/Denning–Fujikawa.

In summary, the numerical simulations indicate that if large numbers of meteoroids were actively ejected from Comet

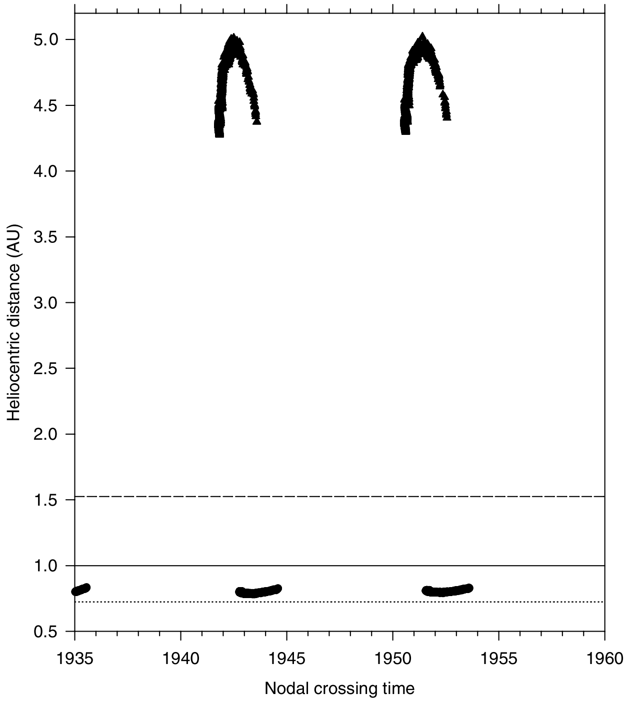

Figure 1. The nodal crossing time of 2000 hypothetical meteoroids ejected during the 1881 return of Comet 72P/Denning–Fujikawa. The nodal distributions correspond to the two returns prior to a close jovian encounter in 1955. The solid line indicates the heliocentric distance of the Earth; the dashed line is the heliocentric distance of Mars; while the dotted line indicates the heliocentric distance of Venus. The descending node points (filled circles) indicate a range of return times (corresponding to a variation of orbital semimajor axes), but only a small variation in heliocentric distance (indicative of nearly constant orbital eccentricity). The stream may well have produced some meteoric activity in the atmosphere of Venus over the time interval shown in the diagram.

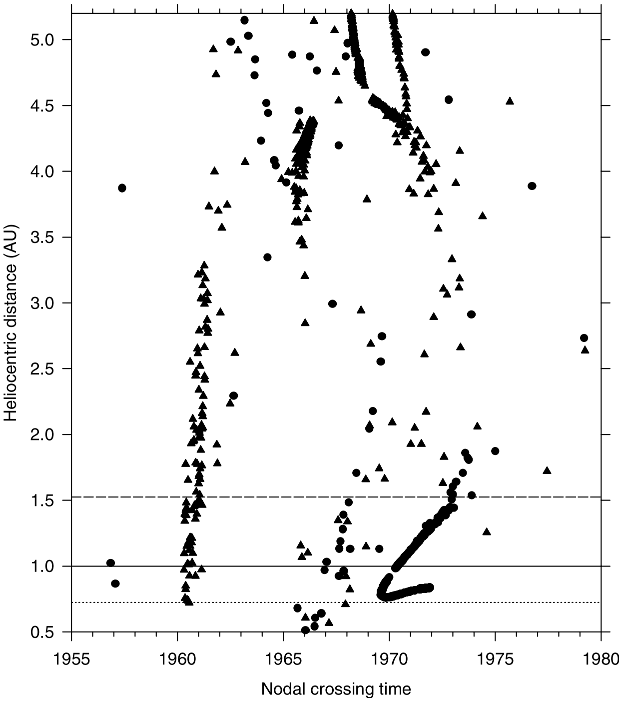

Figure 2. As Fig. 1, but now the nodal distribution is shown after the close jovian encounter in 1955. Clearly the stream coherence has been destroyed during the close Jupiter passage. Interestingly, however, various streamlets of meteoroids are produced, as well as a veritable 'wall' of meteoroids that cuts through the ecliptic, between heliocentric distances of 0.7 and 3.5 au, in one swath in 1961. Some of these meteoroids may have been detected by the Adelaide meteor radar survey. The stream disruption in 1955 results in 1881-ejected meteoroids being potentially sampled by Mars, Earth and Venus.

72P/Denning–Fujikawa during its perihelion return in 1881, then a small fraction of them will potentially be sampled by the Earth in the time interval 1960 to about 2050. We find no indication of the Earth being able to sample meteoroids ejected from the comet during its 1978 perihelion return prior to at least 2110. We note, however, that if copious amounts of meteoroids were ejected in 1978 then a meteor shower may well develop at Venus around 2105. So, at best, it would seem that only very weak meteoric activity is to be expected from Comet 72P/Denning–Fujikawa, with this result being based upon the assumption that many meteoroids were actively ejected during its 1881 perihelion passage.

3 THE ASTEROID BELT DWELL TIME

The main asteroid belt effectively extends from the 4 : 1 to the 3 : 1 resonance positions with Jupiter. As a distinctive region within the Solar system, it offers a veritable 'shooting gallery' for any object that strays into its realm. Indeed, the asteroid size distribution has been sculpted by the numerous collisions between the asteroids within the main belt. Collisions are still occurring to this day and to illustrate this fact just recently, in 1996, asteroid 7968 Elst–Pizarro displayed the consequences of a pummelling by fragments derived from asteroid 427 Galene (Toth 2000). Reach (1992) has also suggested that some of the 'guest stars' recorded in ancient Chinese records were not novae, as is commonly believed, but were rather transient brightenings associated with debris clouds produced during catastrophic asteroid break-up events. The continued collisional processing of objects within the main-belt asteroid region has resulted in a number-to-size distribution that increases with decreasing size, and sooner or later any object that repeatedly strays into the region is going to suffer an impact. The question that we wish to address in this section is what are the impact probabilities for various-sized objects striking Comet 72P/Denning–Fujikawa? We then wish to address the question of the outcome of any potential impacts.

Long-term orbital integrations carried out by Carusi et al. (1985) indicate that over the past 400 years the aphelion distance of Comet 72P/Denning–Fujikawa has remained remarkably stable at about 7.75 au. Its orbital inclination, on the other hand, has shown some variation, being ~3° from the early 1600s to around 1800, and rising steadily thereafter to about 9° at the present epoch. It is clear from its orbital parameters that for each orbit about the Sun, Comet 72P/Denning–Fujikawa passes through the main-belt asteroid region twice. We find that the total dwell time of Comet 72P/Denning–Fujikawa, per orbit, in the main asteroid belt amounts to 0.95 yr, which corresponds to about 10 per cent of its orbital period.

The collision probability per unit time can be calculated via the method outlined by Wetherill (1967). Specifically, the probability that a cometary nucleus of radius R is struck by an object of radius r is

$$\int_{r_{\min}}^{r_{\max}} (\mathrm{d}N/\mathrm{d}r)(R+r)^2 P_i \,\mathrm{d}r,$$

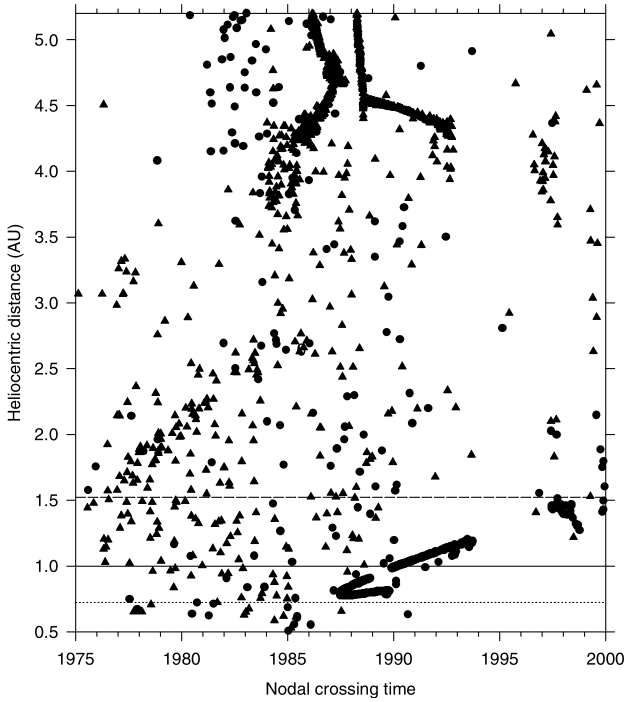

Figure 3. The nodal distribution of hypothetical meteoroids ejected in 1881 during the time interval 1975–2000. Again, we see that the meteoroids are spread out over the entire inner Solar system, and that the Earth will sample at least a few of them, indicative of the possibility of low levels of annual meteoric activity.

where dN is the number of asteroids in the size range r to $r + \mathrm{d}r$, P_i is the intrinsic collision probability, and $r_{\min}$ and $r_{\max}$ correspond to the minimum and maximum impactor sizes. The intrinsic probability is determined from the combined collisional probabilities that result for a given object, with a specified orbit, and all possible minor planet pairings in the main belt. Gil-Hutton (2000) finds that for Comet 72P/Denning–Fujikawa, $P_i = 1.33 \times 10^{-24}\,\mathrm{m^2\,yr^{-1}}$. Asteroid size distribution functions have been published by Bottke et al. (1995), and their results indicate that $\mathrm{d}N/\mathrm{d}r = 6.99 \times 10^{11}/r^{2.95}$ for $r > 87.5$ m and $\mathrm{d}N/\mathrm{d}r = 8.31 \times 10^{12}/r^{3.50}$ for $r < 87.5$ m. The probability of collision clearly decreases rapidly with increasing impactor size, and we cap $r_{\max}$ at 1 km. Table 5 shows the derived probability of collision for various values of $r_{\min}$. As one would expect, the chance of a collision increases with decreasing impactor size. Table 5 indicates that each time Comet 72P/Denning–Fujikawa orbits the Sun, collision with 1-cm-diameter and smaller-sized objects is a near-certainty. Collisions with 1-m-sized objects, however, will probably only occur at intervals of the order of 400 000 yr.

The exact consequences of an impact into the surface material of a comet are unclear at the present time. Kadono (1999) has studied the problem of hypervelocity impacts into low-density material, and has determined empirical formulae for the maximum crater diameter and maximum crater depth. Hypervelocity impact experiments indicate that the maximum crater diameter is only weakly dependent upon the densities of the target and impactor, and to first order

$$D_{\max} = 0.85 D_{\mathrm{P}} V^{1.3},$$

where $D_{\max}$ is the maximum crater diameter, D_{P} is the impactor diameter and V is the collision velocity in $\mathrm{km\,s^{-1}}$.

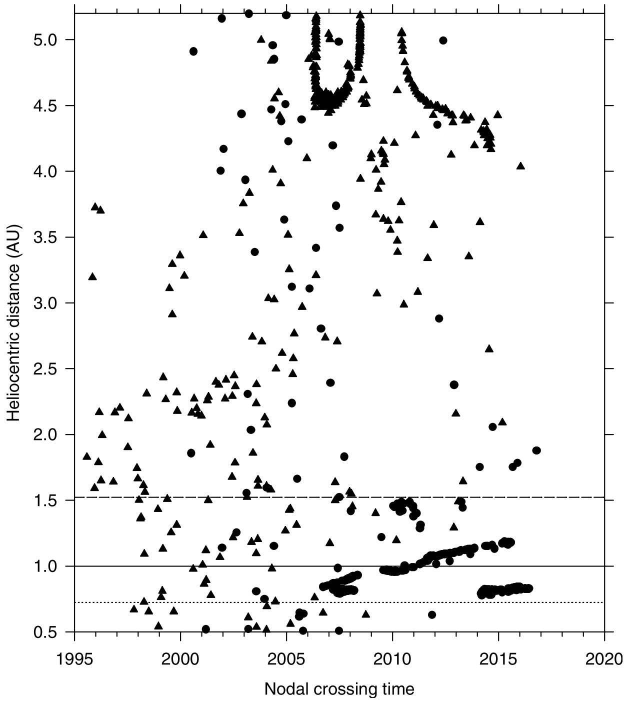

Figure 4. The nodal distribution of hypothetical meteoroids ejected in 1881 during the time interval 1995–2020. In this diagram it can be seen that in 2009 and 2010 the Earth may sample meteoroids from one of the long-lived streamlets produced during the 1955 jovian encounter.

Since we know the orbital parameters of Comet 72P/Denning–Fujikawa, its encounter speed with an asteroid moving along an assumed circular orbit can be calculated directly. We find that the encounter speed at the inner asteroid belt is $19.5\,\mathrm{km\,s^{-1}}$, and the encounter speed at the outer asteroid belt is $15\,\mathrm{km\,s^{-1}}$. At a typical encounter speed of $17\,\mathrm{km\,s^{-1}}$, the maximum impact crater diameter will vary according to $D_{\max} \approx 34 D_{\mathrm{P}}$.

The hypervelocity impact experiments reviewed by Kadono (1999) also indicate that the maximum crater depth, $d_{\max}$, is only weakly dependent upon the velocity, and is mostly determined by the deformation and fragmentation of the impactor. The empirically derived formula given by Kadono (1999) indicates

$$d_{\max} = 2.14 D_{\mathrm{P}} (\rho_{\mathrm{P}}/\rho_{\mathrm{T}})^{1.07},$$

rhere ρ_{P} is the impactor density and ρ_{T} is the target density. Adopting an impactor density of $3000\,\mathrm{kg\,m^{-3}}$ and a target density of $500\,\mathrm{kg\,m^{-3}}$, the maximum crater depth will be of the order of $d_{\max} = 14.5 D_{\mathrm{P}}$.

The results presented by Kadono (1999) – and summarized above – suggest that a 1-cm-diameter object striking Comet 72P/Denning–Fujikawa while in the main-belt asteroid region will produce a crater some 34 cm in diameter and 14.5 cm deep. A 1-m-diameter impactor will produce a crater 100 times larger than the 1-cm impactor. As we saw above, the impact probabilities are such that Comet 72P/Denning–Fujikawa is likely to be struck by at least one 1-cm-sized object each time it orbits the Sun. Over a time-span equivalent to 10 perihelion passages, the largest object that the comet is likely to encounter will be about 4 cm in diameter. This latter impactor might produce a crater that is 1.4 m in diameter and 0.6 m deep.

We do not know what fraction of the nuclear surface was active for Comet 72P/Denning–Fujikawa during its perihelion returns in

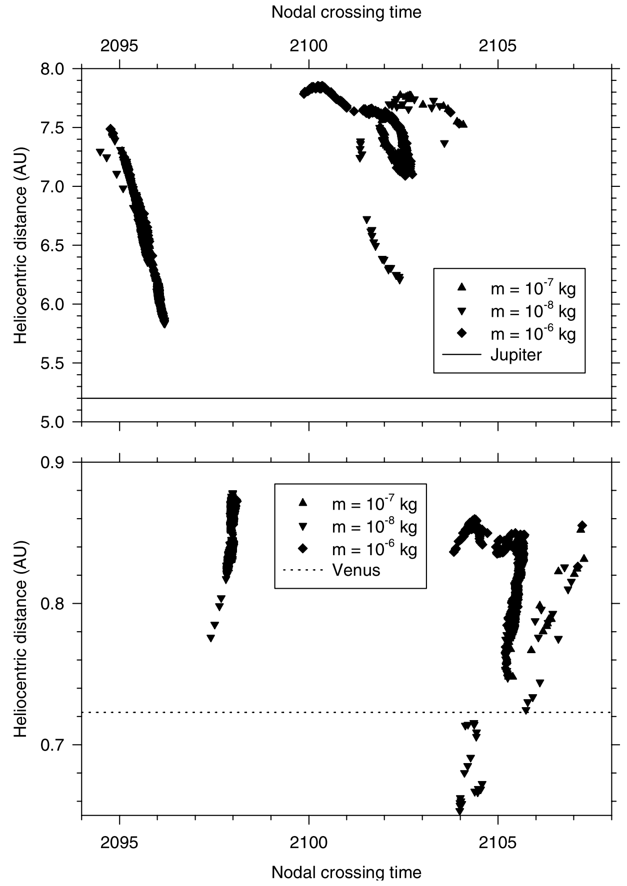

Figure 5. The nodal distribution of hypothetical meteoroids ejected from Comet 72P/Denning–Fujikawa in 1978. The symbols for both diagrams are upward-pointing filled triangles for 10^{-7}-kg meteoroids, filled diamonds for 10^{-6}-kg meteoroids and downward-pointing filled triangles for 10^{-8}-kg meteoroids. Meteoroids ejected in 1978 tend to acquire nodal points that, over time, drift outwards from the orbit of Jupiter (solid line at 5.2 au in the top diagram). While the meteoroids do not become Earth-orbit-crossing before at least 2110, a meteor shower may well be produced in the upper atmosphere of Venus (dashed line in lower diagram) in around 2105.

Table 5. Impact probabilities for Comet 72P/Denning–Fujikawa as a function of impactor radius. The probabilities are presented as percentages per orbit and for an assumed nuclear radius of 1 km.

$r_{\min}$ (m)	P(per cent per orbit)
0.01	42.00
0.02	7.4
0.05	0.8
0.10	0.1
0.50	2.3×10^{-3}
1.00	4.2×10^{-4}

1881 and 1978. Luu (1994) has summarized the data pertaining to other cometary nuclei, however, and her table 2 indicates that some 0.1–1 per cent of the nuclear surface is actively undergoing sublimation at any given time. At ~10 per cent active area Comet 1P/Halley appears to be an exception, but any general statements about surface activity are clearly provisional given the great paucity of actual data. Since Comet 72P/Denning–Fujikawa was intrinsically faint in both 1881 and 1978, we might assume that at most 0.1 per cent of its surface was active. For illustrative purposes let us assume a nuclear radius of 1.0 km and a 0.1 per cent active area. These assumptions result in an exposed surface are of $\sim1.5\times10^{4}\,\mathrm{m}^{2}$. Also, if for the sake of argument we assume that any impact crater would be cylindrical in shape (with diameter $D_{\max}$ and depth $d_{\max}$), then the required 'surface exposure' could be produced through the impact of a single 2-m-diameter object. According to Table 1, however, we would expect only one such collision per 2×10^{6} yr time interval. The time between impacts with 2-m-diameter objects is some 10–100 times longer than the expected lifetime of an inner Solar system comet (Olsson-Steel 1987). It would seem unlikely therefore that the cometary activity observed during both the 1881 and 1978 returns of Comet 72P/Denning–Fujikawa was the direct result of impacts sustained from metre-sized objects. This being said, one can never entirely rule out the possibility of actually observing statistically rare events. Indeed, with respect to observing statistically unlikely events one need look no further than the outburst of Comet 1P/Halley recorded on 1991 February 12 when it was 14.3 au from the Sun. This particular outburst was most probably the result of a collision between the comet and a small asteroid-like object (Hughes 1991).

4 DISCUSSION

Drummond (1981) includes Comet 72P/Denning–Fujikawa amongst his list of 'silent' comets. We have found, however, that the meteoric 'reticence' of Comet 72P/Denning–Fujikawa comes about not because it does not actively eject meteoroids, but because it appears that the most important controlling factor for meteoroid evolution is gravitational scattering by Jupiter. This was certainly the case for any meteoroids that might have been ejected in 1881. At other ejection epochs, as exemplified by the 1978 return, the meteoroids appear to acquire relatively stable orbital configurations with no Earth-orbit intercepts occurring on time-scales of the order of at least 100 yr. In addition to the dynamical restrictions, the small size of the nucleus of Comet 72P/Denning–Fujikawa also argues against the development of a prominent meteor shower; in general, a small nucleus implies a faint, low-activity comet that ejects relatively small amounts of meteoric material.

Kresak (1991) counts Comet 72P/Denning–Fujikawa among his list of 'lost and then found again' comets, and it seems that we are observing an old, transitional comet heading, at least observationally, towards minor-planet status. The comet has only been observed twice and has otherwise been conspicuous by its absence (in the sense of observed cometary activity) during at least five perihelion returns in the past century (Kresak 1991; and Table 2). It is generally believed that cometary activity decreases with cometary age because of the build-up of an inert surface mantle (Brin & Mendis 1979; Luu 1994), but, as Comet 72P/Denning–Fujikawa indicates, it is by no means a linear decay process. The basic idea behind the ageing process is that non-volatile material accumulates on the surface of the cometary nucleus, and it is this accumulate that results in the choking-off of sites of active sublimation with the effect of reducing cometary activity. It is not entirely clear, however, how the surface mantle actually develops. Hughes (2000a), for example, has argued that comets should be very efficient at clearing away surface material. We also note that the low surface gravity associated with the apparent small size of the nucleus of Comet 72P/Denning–Fujikawa does not favour surface mantle build-up. Williams et al. (1993) and Hughes (2000b), however, have outlined an interesting ageing model in which surface activity is modified through surface grooming and compaction by numerous collisions between the cometary nucleus and sibling meteoroids ejected at earlier epochs. The idea is that the continual surface pummelling by small meteoroids will result in surface inhomogeneities, and this will in turn modify surface activity. The calculations presented in Section 3 also suggest that the many small-particle impacts resulting from the repeated passage of Comet 72P/Denning–Fujikawa through the main asteroid belt might also enhance the surface grooming processes.

While there are numerous possible processes by which cometary activity might be modified, it does seem clear that cometary nuclei are active over only a small fraction of their surface, and (it is presumed) that as they age the fractional area that is active decreases. Cometary ageing, however, is by no means a simple choking-off process, as exemplified by Comet 72P/Denning–Fujikawa, and outbursts of intermittent activity can apparently occur. Unfortunately, the cometary outburst and rejuvenation mechanisms are as poorly understood as the cometary ageing mechanisms. Hughes (1991), however, has outlined a number of processes that might lead to the temporary re-activation of an old comet. Of the mechanisms discussed by Hughes (1991), the one that seems most suited to Comet 72P/Denning–Fujikawa (although admittedly many are possible) is that of surface modification through impacts. The comet has a small orbital inclination and spends about 1 yr per orbit in the main-belt asteroid region (an illustration of the orbit can be found at http://cfa-http://www.harvard.edu/iau/plot/0072P.gif). We have found, however, that the 1978 outburst–recover of Comet 72P/Denning–Fujikawa was probably not due to the simple impact exposure of previously ‘covered’ ices. During the apparently dormant interval between 1881 and 1978, the largest object probably to strike the nucleus of the comet, while it was passing through the main-belt asteroid region, would have been about 4 cm in diameter. While such an object would not produce a cavity large enough to drive any significant cometary activity, it might, none the less, act as the catalyst for an outburst. Matese & Whitman (1994), for example, have invoked small meteoroid collisions as a possible mechanism for triggering cometary outbursts. In particular, they suggest that multiple small meteoroid impacts might cause the weakening of a subsurface crystalline layer, which ultimately buckles to release pre-existing pockets of trapped gas explosively (see also Gronkowski & Smela 1998). Large areas of newly exposed ice will then result from the eruption of the trapped gases. However, there is much that is still unclear about the ‘trapped gas’ outburst model, and, until a better understanding of how comets are actually constructed becomes available (e.g. via *in situ* observations), the problem remains an obscure one.

In summary, there are mixed signs as to whether we should expect to see any associated meteoric activity from Comet 72P/Denning–Fujikawa, but if material was actively ejected in 1881 then some of it may have become Earth-orbit-crossing after 1960–61. It is also possible that enhanced meteor displays might be realized from the 1881-ejected material in 2009 and 2010, but this possibility requires further detailed study. In general, however, it appears that the orbital characteristics of the parent comet are not conducive to the formation of a long-lived coherent stream of meteoroids with Earth-intercept parameters. The orbital characteristics of Comet 72P/Denning–Fujikawa are such that it traverses the main-belt asteroid region twice per orbit, and during each passage it is certain to collide with centimetre-sized objects. The typical impact speed will be some $17\,\mathrm{km\,s^{-1}}$, but only small metre-sized impact craters are likely to result from such collisions.

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