A&A 394, 311–316 (2002)
DOI: 10.1051/0004-6361:20021099
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Astronomy
&
Astrophysics

The velocity distribution of periodic comets and the meteor shower on Mars

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Received 10 September 2001 / Accepted 29 July 2002

Abstract. The collision velocities with Mars of the known periodic comets with perihelion distances less than the orbital radius of Mars 1.52 au are calculated and statistically analyzed. The velocity distribution shows that short-period comets usually have smaller collision velocities than the long-period comets whether they are numbered or unnumbered. For comets with period $P \leq 270$ y, most collision velocities with Mars are less than 30 km s^{-1}. These velocities are smaller than the corresponding collision velocities with Earth. Based on the similarity of the velocity distributions of the comets and meteoroid streams, meteor showers on Mars are discussed briefly.

Key words. celestial mechanics – comets: general – meteors, meteoroids

1. Introduction

It is well known that comets, as they near the perihelion of their orbits, release large numbers of dust grains (Kirkwood 1861) due to the normal process of gas ejection. These particles, namely meteoroids, leave the cometary nucleus at speeds which are significantly less than the orbital velocity of the comet (Whipple 1951). In consequence, these meteoroids move on almost the same orbits as the parent comets, gradually drifting ahead and behind the comet because of small differences in orbital period. After a time interval of a few tens of cometary periods, the meteoroids will have spread all the way around the cometary orbit (Steel 1994; Williams 1996). At this stage, meteors (which are produced by the impact of the stream meteoroids with the atmosphere of the Earth) can be observed whenever the Earth passes through the cometary nodes. In principle, there could also be meteor showers on Mars or any other planets with an atmosphere whenever the planet encounters a meteoroid streams.

Meteoroids strike the Earth with a velocity that is similar to the orbital velocity, that is, several tens of kilometers per second. At such velocities, dust impacts can affect all phases of spacecraft operation (Beech et al. 1995, 1997; McBride 1997; McBride & McDonnell 1999). For example, the *Mir-1* solar panels were damaged on the night of the Perseid meteor shower maximum (Lenorovitz 1993). The ESA Olympus communications satellite may have been disabled by a Perseid meteoroid (Caswell et al. 1995). As Mars exploration is entering its second era, Mars-orbiting spacecraft and ground operations, both manned and unmanned, are similarly vulnerable to meteoroid impact. In addition to this potential danger, meteor shower on Mars are of scientific interest. Mars may be an ideal vantage point to view meteors, with emphasis on determining the compositions and structures of meteoroids and comets with perihelia beyond Earth's orbit (Adolfsson et al. 1996; Christou & Beurle 1999; Treiman & Treiman 2000). The undertaking of missions to Mars brings an opportunity to extend our knowledge of the meteoroid stream complex to a wide range of the heliocentric distances.

As the meteoroid stream orbit and the orbit of the parent comet are very similar, the velocities of both at one astronomical unit should be very similar. Unfortunately, most comets do not produce meteoroid streams that can be intersected by the Earth while many of the minor meteor showers do not have an identified parent comet. For this reason, Hughes & Williams (2000) have investigated the velocity distributions of comets and meteor streams, and found these to be very similar. They found that the velocities of short-period comets at Earth are generally small. As the distributions were similar, they concluded that the meteor population did mainly come from the short period comets. Most comets do not of course collide with Mars, nor indeed with the Earth. In this paper, we calculate the velocity that periodic comets would have on impact with Mars having adjusted the argument of perihelion so as to make such a collision possible. We investigate the distribution of these velocities and briefly discuss the implications for meteor showers on Mars.

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2. Comet-Mars collision velocity

As already mentioned, we are going to adjust the argument of perihelion, ω, of cometary orbits so that the heliocentric distance of the node, r_N, is equal to 1.52 au. Clearly one can only do this for those comets whose perihelion distance is less than 1.52 au, and whose aphelion distance is greater than this value. Hence we search through the catalogue given in Marsden & Williams (1996) and select all comets that satisfy the above. For each selected orbit, the change in ω required to make the nodal distance 1.52 au is then calculated and a new orbit is defined with the correct value of ω. In reality, changes in the argument of the perihelion can introduce secular changes in the orbital inclination and the eccentricity. We shall ignore this since it is hard to calculate and is unlikely to alter the distribution of velocities, though of course changing individual values.

Assuming Mars moves in the ecliptic plane and its orbit is circular, the comet-Mars collision velocity V is given as (Hughes & Williams 2000)

$$\begin{aligned} V^2 &= GM_\odot\left[\frac{3}{r_\mathrm{m}} - 2\cos i\left(\frac{p}{r_\mathrm{m}^3}\right)^{0.5} - \frac{1}{a}\right] \\ &= \frac{GM_\odot}{r_\mathrm{m}}\left[3 - 2\left(\frac{q(1+e)}{r_\mathrm{m}}\right)^{0.5}\cos i - \frac{r_\mathrm{m}}{q}(1-e)\right], \qquad (1) \end{aligned}$$

where G is the constant of gravitation, $M_\odot$ is the mass of the Sun and r_m is the heliocentric distance of Mars. i, p, e, a and q are the inclination, semi-parameter, eccentricity, semi-major axis and perihelion distance of the cometary orbit, respectively.

In fact, the orbit of Mars has an eccentricity of 0.0934 and an inclination of $1\overset{\circ}{.}85$. Any resultant small changes in the values of individual impact velocities do not affect the distribution of these velocities in a systematic fashion (Babadzhanov & Obrubov 1992) and so we shall not correct for this.

As $G = 6.6726\times10^{-11} N\mathrm{m}^2\mathrm{kg}^{-2}$, $M_\odot = 1.9891\times10^{30}$ kg and $r_\mathrm{m} = 1.52$ au $= 1.52\times1.4960\times10^{11}$ m, Eq. (1) becomes

$$V^2 = 582.24\left[3 - 2\left(\frac{q(1+e)}{r_\mathrm{m}}\right)^{0.5}\cos i - \frac{r_\mathrm{m}}{q}(1-e)\right]\ \mathrm{km}^2\ \mathrm{s}^{-2}. \qquad (2)$$

In order to calculate the true impact speed with Mars, V_i, the effect of the gravitational field of Mars has to be taken into account. Hence, a term of $2GM_\mathrm{m}/R_\mathrm{m} = 25.28\ \mathrm{km}^2\ \mathrm{s}^{-2}$ is added to Eq. (2), where M_m and R_m are the mass and radius of Mars, respectively, giving the true comet-Mars impact velocity V_i as

$$\begin{aligned} V_i^2 &= 25.28 + 582.24\left[3 - 2\left(\frac{q(1+e)}{r_\mathrm{m}}\right)^{0.5}\cos i \right. \\ &\quad \left. - \frac{r_\mathrm{m}}{q}(1-e)\right]\ \mathrm{km}^2\ \mathrm{s}^{-2}. \qquad (3) \end{aligned}$$

Using Eq. (3), we calculate the comets-Mars impact velocities of all comets within the correct perihelion and aphelion range that have data given in Marsden & Williams (1996). In Table 1 we give the results for all numbered periodic comets that have more than one recorded perihelion passage and where the perihelion distance is less than 1.52 au.

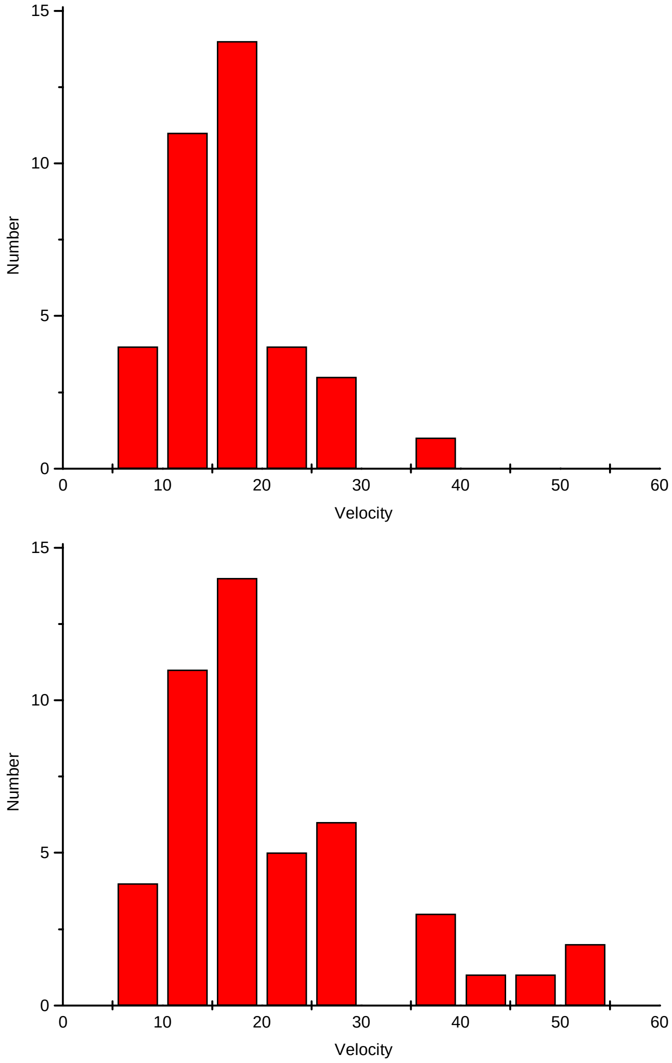

Fig. 1. The upper histogram is the distribution of impact velocities of the 37 numbered periodic comets given in Table 1 that have $P < 20$ y. The lower histogram is the distribution of impact velocities of all the 47 numbered periodic comets given in Table 1.

In Table 2 the results are given for the unnumbered periodic comets similarly selected. In addition, 6 comets are included (and denoted with the symbol "$*$") that have been discovered since 1996 and the data for these are taken from Minor Planet Center (MPC) web site.

Inspection of Table 1 shows that the impact velocities of most of the short-period comets are smaller than those of the long-period comets. The mean impact velocity of the 37 comets with a period less than 20 y is 16.70 km s^{-1} while the median impact velocity is 15.86 km s^{-1}. The corresponding mean value for all the comets in Table 1 is 21.07 km s^{-1} while the median impact velocity is 17.31 km s^{-1}. All these values are smaller than the corresponding values on Earth as found by Hughes & Williams (2000), and is not unexpected as the Keplerian velocity decreases with heliocentric distance.

Figure 1 shows two histograms of the number of comets as a function of impact velocity. The lower histogram is for all the comets given in Table 1, while the upper histogram is for the sub-set of comets in Table 1 that have a period less

Table 1. The calculated impact velocities, V_i, between Mars and those numbered periodic comets given in Marsden & Williams (1996) which have perihelion distance $q < 1.52$ au and have been observed at more than one apparition. The orbital inclinations and eccentricities are denoted by i and e. V is the velocity before adding the contribution from the acceleration due to the gravitational field of Mars.

comet name	Period (y)	q (au)	e	i (deg)	V km s^{-1}	V_i km s^{-1}
2P	3.28	0.331396	0.850013	11.92940	24.95	25.45
107P	4.30	1.000483	0.621670	2.78298	14.53	15.37
26P	5.11	0.996811	0.663805	21.08677	17.72	18.42
79P	5.21	1.200685	0.600768	2.93945	12.07	13.07
141P	5.22	0.748904	0.751085	12.81261	19.96	20.58
96P	5.24	0.124718	0.958636	60.07425	34.93	35.29
45P	5.27	0.532052	0.824241	4.24838	22.95	23.49
25D	5.43	1.270041	0.586849	5.36573	7.93	9.39
73P	5.43	0.932772	0.694815	11.42359	17.14	17.86
5D	5.46	0.589847	0.809796	29.3821	24.73	25.23
41P	5.46	1.065309	0.656365	9.22518	14.96	15.78
46P	5.46	1.063764	0.656748	11.72252	15.30	16.10
124P	5.46	1.412895	0.554250	31.47086	16.57	17.31
10P	5.47	1.481680	0.522817	11.97670	8.65	10.00
9P	5.50	1.500048	0.518953	10.54134	7.89	9.36
88P	5.57	1.406129	0.552672	4.39838	8.64	10.00
37P	6.13	1.446019	0.568121	7.16277	8.50	9.88
104P	6.18	1.396623	0.585207	15.48913	11.43	12.49
7P	6.31	1.255891	0.634425	22.30141	15.43	16.23
103P	6.39	1.031722	0.700375	13.61887	16.57	17.32
6P	6.51	1.345814	0.614046	19.52380	13.49	14.40
67P	6.59	1.300033	0.630193	7.11331	11.47	12.52
21P	6.61	1.033732	0.706472	31.85878	20.75	21.35
49P	6.61	1.368590	0.611541	18.29066	12.83	13.78
3D	6.62	0.860265	0.755879	12.5500	19.06	19.71
62P	6.64	1.495854	0.576610	10.49530	8.51	9.88
112P	6.64	1.457862	0.587773	24.20476	13.67	14.57
15P	6.67	1.035557	0.710304	3.67366	15.67	16.46
18P	6.72	1.292928	0.638584	17.83226	13.84	14.72
19P	6.88	1.365123	0.622803	30.27070	17.00	17.73
24P	8.22	1.205005	0.704809	11.75148	14.34	15.20
58P	8.24	1.381169	0.661426	13.47858	11.81	12.84
72P	9.01	0.790200	0.817792	9.12682	20.64	21.24
64P	9.21	1.338894	0.694590	8.43693	11.78	12.81
85P	11.23	1.158161	0.774364	4.87674	15.05	15.87
8P	13.51	0.997734	0.824088	54.69256	29.24	29.67
66P	14.97	1.274280	0.787683	18.70094	15.82	16.60
27P	27.41	0.747872	0.918742	28.95677	25.72	26.21
55P	33.22	0.976585	0.905504	162.48615	53.74	53.97
20D	61.86	1.254043	0.919829	40.88769	24.15	24.67
13P	69.56	1.175501	0.930295	44.66567	26.14	26.62
23P	70.54	0.478751	0.971952	19.33387	28.81	29.25
12P	70.92	0.780779	0.954604	74.19157	36.06	36.41
122P	74.36	0.658892	0.962738	85.39111	40.13	40.44
1P	76.00	0.587104	0.967277	162.24220	51.60	51.84
109P	135.0	0.958217	0.963589	113.42664	47.20	47.47
35P	154.9	0.748490	0.974050	64.20652	34.89	35.25

than 20 years. It can be seen that the impact velocities of the short-period comets ($P < 20$ y) are less than 30 km s^{-1} and most lie between 10 and 20 km s^{-1}. The impact velocities of all the comets with $P > 20$ y (the Halley-family comets) are larger than 20 km s^{-1}. In fact the velocities all lie in the range 24.67 km s^{-1} $\leq V_i \leq$ 53.98 km s^{-1}.

The velocity distribution of the unnumbered comets given in Table 2 shows the same characteristic as the numbered

Table 2. The calculated impact velocities, V_i, between Mars and those un-numbered periodic comets given in Marsden & Williams (1996) which have perihelion distance $q < 1.52$ au. The orbital inclinations and eccentricities are denoted by i and e. V is the velocity before adding the contribution from the acceleration due to the gravitational field of Mars.

comet name	Period (y)	q (au)	e	i (deg)	V km s^{-1}	V_i km s^{-1}
D/1766 G1	4.35	0.40603	0.84763	7.865	24.58	25.09
D/1819 W1	5.10	0.892318	0.698752	9.1081	17.33	18.05
P/1994 P1-A	5.23	0.752548	0.750145	12.7865	19.91	20.53
P/2000 G1∗	5.31	1.002858	0.670589	10.3592	15.94	16.72
D/1884 O1	5.38	1.279482	0.583252	5.4701	10.63	11.76
D/1886 K1	5.44	1.325273	0.571388	12.6710	11.47	12.52
D/1770 L1	5.60	0.674449	0.786119	1.5517	20.74	21.35
D/1783 W1	5.89	1.459289	0.552456	45.1277	21.74	22.32
D/1978 R1	5.97	1.101411	0.665248	5.9464	14.36	15.22
D/1978 C2	6.35	1.438494	0.580362	7.0388	8.73	10.08
D/1892 T1	6.52	1.432189	0.589631	31.2608	16.61	17.35
P/1999 RO28∗	6.63	1.231769	0.650817	8.1914	12.79	13.75
D/1896 R2	6.65	1.454747	0.588483	11.3507	9.47	10.72
P/1986 W1	6.75	1.457305	0.592020	1.5285	7.87	9.34
P/1998 W2∗	6.91	1.420189	0.608385	21.9293	13.40	14.31
D/1895 Q1	7.20	1.297763	0.652013	2.9923	11.38	12.44
P/1994 A1	7.37	1.367310	0.638830	4.1845	10.20	11.37
D/1894 F1	7.40	1.147000	0.697887	5.5274	14.24	15.10
P/1991 V1	7.55	1.132346	0.705642	16.8548	16.17	16.93
D/1984 W1	7.84	1.319698	0.665667	21.5677	14.87	15.70
P/1994 X1	18.2	1.276890	0.815684	29.0741	19.06	19.71
P/1983 V1	21.5	1.282459	0.833912	95.7312	42.15	42.45
P/1991 L3	51.3	0.982524	0.928807	19.1904	21.35	21.94
D/1827 M1	57.5	0.806508	0.945838	136.4601	50.44	50.69
D/1921 H1	63.3	1.114978	0.929088	22.3265	20.26	20.87
D/1989 A3	81.9	0.420271	0.977708	83.0672	39.95	40.26
D/1942 EA	85.4	1.287079	0.933639	37.9961	22.98	23.53
D/1917 F1	145	0.190186	0.993121	32.6828	35.01	35.37
D/1889 M1	145	1.104894	0.960033	31.2468	22.97	23.52
D/1984 A1	151	1.357455	0.952214	51.8009	27.67	28.13
C/1999 K4∗	155	1.444801	0.949944	120.9922	50.31	50.56
D/1937 D1	187	0.618937	0.981098	26.0205	27.94	28.39
C/1905 F1	226	1.114641	0.969961	40.1989	25.59	26.08
C/1857 O1	235	0.746843	0.980414	32.7565	27.54	30.00
C/1855 L1	252	0.567564	0.985780	156.8707	51.43	51.68
C/1932 Y1	262	1.130788	0.972386	24.5025	21.05	21.64
C/1984 U2	270	1.214510	0.970905	13.8812	17.57	18.27
C/1885 R1	275	0.749149	0.982264	59.0970	33.69	34.07
C/1840 U1	286	1.479951	0.965941	57.9043	28.59	29.03
C/1979 Y1	291	0.987598	0.545164	148.6018	48.30	48.56
C/1932 P1	291	1.037198	0.976369	71.7195	36.09	36.44
C/1932 G1	302	1.254431	0.972127	74.2776	36.40	36.75
C/1941 B1	355	0.941864	0.981221	26.2756	23.95	24.47
C/1955 L1	356	0.534419	0.989361	86.5016	40.86	41.17
C/1931 O1	357	1.046903	0.979203	42.2957	26.92	27.38
C/1964 N1	391	0.821752	0.984643	171.9200	54.06	54.30
C/1979 S1	391	1.432081	0.973197	67.0840	33.36	33.73
C/1861 J1	409	0.822384	0.985070	85.4424	40.43	40.74
C/1861 G1	415	0.920700	0.983465	79.7733	38.79	39.11
C/1898 F1	419	1.095261	0.980454	72.5292	36.25	36.59
C/1940 O1	425	1.082228	0.980843	54.6906	30.39	30.84
C/1975 T1	446	0.838047	0.985653	118.2332	48.03	48.30
C/1930 F1	485	0.481810	0.992194	67.1409	37.06	37.40
C/1843 D1	513	0.005527	0.999914	144.3548	42.59	42.88

Table 2. continued.

C/1846 J1	538	0.633760	0.990414	150.6809	51.55	51.79
C/1974 O1	551	1.372951	0.979579	173.1585	57.25	57.47
C/1906 V1	583	1.212686	0.982624	56.3891	30.40	30.81
C/1998 K5∗	617	0.963547	0.986701	9.9271	21.18	21.77
C/1952 H1	645	1.282696	0.982816	112.0282	47.95	48.21
C/1882 R1A	669	0.007750	0.999899	142.0113	42.75	43.05
C/1985 T1	700	1.317140	0.983297	139.0692	53.73	53.97
C/1992 W1	719	0.664134	0.991721	115.1232	46.86	47.13
C/1987 B2	724	0.393020	0.995125	40.8543	33.22	33.60
C/1961 T1	759	0.681129	0.991812	155.7107	52.32	52.56
C/1886 H1	768	0.269803	0.996783	87.6615	41.33	41.63
C/1853 G1	781	0.908693	0.989286	122.1955	49.11	49.37
C/1997 O1∗	812	1.371801	0.984235	115.8021	49.13	49.39
C/1965 S1-A	880	0.007786	0.999915	141.8642	42.77	43.07
C/1936 O1	888	0.518403	0.994389	121.9417	47.38	47.64
C/1935 A1	901	0.811148	0.991304	65.4251	35.19	35.55
C/1963 R1	903	0.005065	0.999946	144.5821	42.60	42.89
C/1963 A1	932	0.632139	0.993377	160.6487	52.31	52.55
C/1894 G1	958	0.983032	0.989884	86.9666	40.84	41.15

comets in Table 1, namely that the impact velocities of the short-period comets are systematically less than for the long-period comets. The mean impact velocity of the 37 comets with a period less than 270 years is 14.41 km s^{-1} with the median impact velocity of 20.53 km s^{-1}. For all the comets in Table 2, the mean impact velocity is 30.64 km s^{-1} and the median is 30.84 km s^{-1}.

Figure 2 shows two histograms of the number of comets as a function of impact velocity. The upper one is for the 37 comets with $P \leq 270$ y in Table 2 and the lower histogram is for remaining 38 comets in Table 2. The velocity distribution in the upper histogram is similar to the histogram for all the numbered comets shown in Fig. 1, with most of the calculated impact velocities lying in the range between 10 and 25 km s^{-1}. For the 38 comets shown in the lower histogram, the impact velocities are all larger than 20 km s^{-1} and most in fact lie between 30 and 55 km s^{-1}.

Looking in more detail at Tables 1 and 2, we find the high impact speed is associated with high orbital inclination. The reason for this is easy to see from Eq. (3). There is one term in the equation $(2(\frac{q(1+e)}{r_{\rm m}})^{0.5}\cos i)$ that is large and negative for small values of i, but decreases with increasing i and becomes positive when $i > \pi/2$. Most short period comets have low inclinations and long period comets generally have high inclinations. Hence, though there is no direct connection between period and impact velocity, it is still true that a high impact velocity will only arise from long period comets.

3. Meteor shower on Mars

Meteors are the visible effects produced by the ablation of a meteoroid following its impact with the upper atmosphere. Meteor showers are the consequence of the Earth intersecting a stream of meteoroids and we have already outlined the connection between meteoroid streams and comets. The height in the atmosphere at which meteoroid ablate depends on the atmospheric density and the impact velocity. If we accept the conclusions of Hughes & Williams (2000) that the impact velocity of comets and meteoroids are similar and also compare their velocity distribution with ours as found above, we conclude that meteoroids will impact Mars with a slightly lower velocity than with the Earth. The atmosphere of Mars is thinner than that of the earth, but does not decay as rapidly and, perhaps by coincidence, the two effects essentially cancel each other so that, according to Adolfsson et al. (1996), meteoroids will ablate on Mars at a height of about 120 km, essentially the same height as where ablation takes place on Earth. Hence, meteor showers should be visible on Mars just as on Earth. The brightness of a meteor is related to the impact velocity as well as meteoroid radius and density. Hughes (1978), Hughes & Williams (2000) gives the magnitude of a meteor as

$$M = A - B\log m - C\log V_i \tag{4}$$

where M is the zenithal visual magnitude of the meteor, m (g) is the mass of the causative meteoroid and V_i (km s^{-1}) is the impact velocity of the meteoroid with the atmosphere. A, B and C are constants which are dependent on the model of atmosphere.

Hence, we should expect the magnitude of a meteor on Mars to be larger (ie the meteor fainter) than a meteor caused by an identical meteoroid on Earth. Hence, we should expect to see fewer visible meteors as the many faint meteors seen on Earth would not be observable on Mars. Adolfsson et al. (1996) has investigated this in some detail and showed that meteoroids with speed ($\geq$30 km s^{-1}) would produce meteors of similar brightness in the atmospheres of both Earth and Mars; lower speed meteoroids would however be fainter in Martian atmosphere.

In Tables 1 and 2, there are 12 comets among the comets with period <200 year that have a calculated impact speed with Mars $\geq$30 km s^{-1} . Of course, many of the comets with longer periods also have a large impact velocities with Mars, but long period comets are not generally associated with known meteoroid stream at Earth, probably because the time interval over

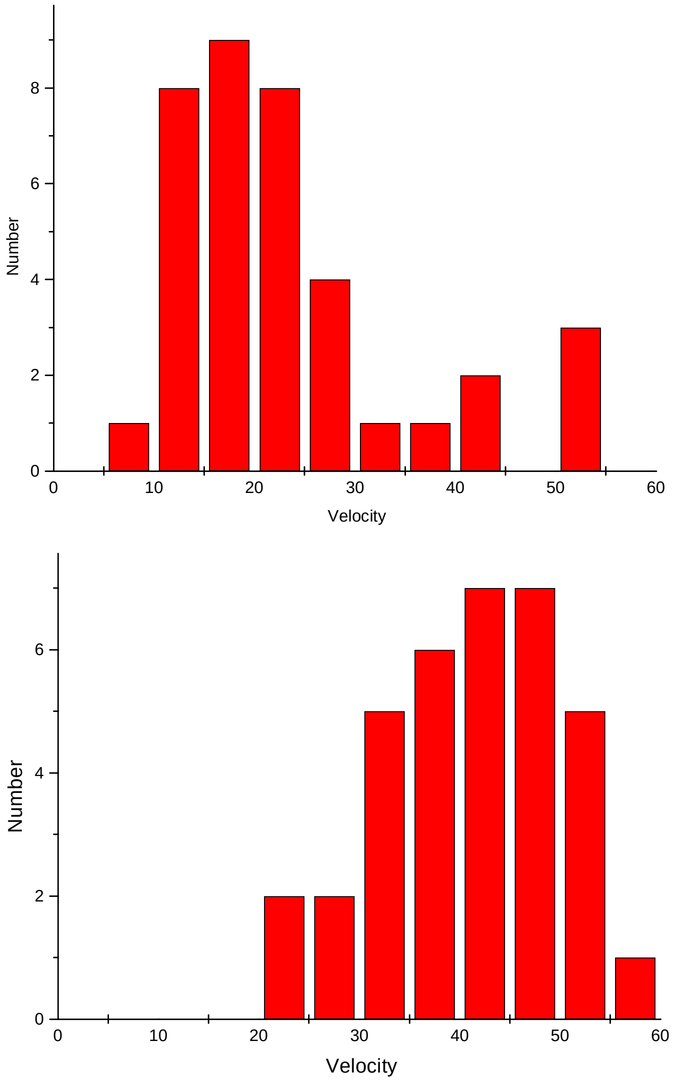

Fig. 2. These histograms show the distribution of impact velocities of the unnumbered periodic comets given in Marsden & Williams (1996) that have $q < 1.52$ au. The upper is for 37 comets with orbital period $P \leq 270$ y, and the lower for the remaining 38 comets with $270 < P < 960$ y.

which the comet is active and so producing meteoroids is very short compared to the orbital period. Any potential stream dissipates long before the meteoroids can spread along the orbit.

We also note that in producing the results reported in Tables 1 and 2, the argument of perihelion was artificially adjusted so as to force the orbit to cross the ecliptic at 1.52 au. Many of these cometary orbits do not in reality pass close to Mars. Hence, it is incorrect to imagine that all the comets listed will produce a visible meteor shower on Mars if the impact velocity is in the correct range of values. Using the real orbits, Christou & Beurle (1999) identified only 1P/Halley and 13P/Olbers as comets that potentially likely to generate bright meteors on Mars. Treiman & Treiman (2000) suggested that 45P/Honda-Mrkos-Pajdusakova should be added to this list of comets that can produce bright Martian meteors.

However, we must also remember that in order to cause many of the potential catastrophes mentioned in the introduction, the meteor does not need to be bright. Many more comets pass close to the Martian orbit than pass close to Earth's orbit. Of the periodic Mars-crossing comets, 56 approach Mars' orbit within 0.15 au (Treiman & Treiman 2000). This suggests that Mars may experience many more faint meteor showers than Earth. These can be detected by radio and in future missions to Mars, a radio detector should be included on the payload so that the risk of damage to equipment in the Martian environment can be properly assessed.

Acknowledgements. We are gratefully to acknowledge M. Fulle for his suggestions and comments which helped to improve this paper. Yuehua Ma would like to acknowledge the support of the National Natural Science Foundation of China (No. 19873020), National Science Council of Taiwan (NSC-90-2816-M-008-0002-6), the Minor Planetary Foundation of Purple Mountain Observatory and the Scientific Research Funding for the Returned Overseas Chinese Scholars, State Personnel Ministry. Yuehua Ma and Wenping Chen would like to acknowledge the support of the grant NSC90-2112-M-008-021.

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