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ASTEROID FLUX AND IMPACT CRATERING RATE ON VENUS. E.M. Shoemaker, R.F. Wolfe, and C.S. Shoemaker, U.S. Geological Survey, Flagstaff, AZ 86001.

By the end of 1990, 65 Venus-crossing asteroids had been recognized (Table 1); these represent 59% of the known Earth-crossing asteroids. Further studies, chiefly numerical integrations of orbit evolution, may reveal one or two more Venus crossers among the set of discovered asteroids. We define a Venus crosser as an asteroid whose orbit can intersect the orbit of Venus as a result of secular (long range) perturbations. Venus crossers revolving on orbits that currently overlap the orbit of Venus are here called Venapol asteroids, and those on orbits that don't overlap are called Venamor asteroids; we recognize 42 Venapols and 23 Venamors.

Collision probabilities with Venus for 60 of the known Venus crossers have been determined by the methods described in [1]. The mean collision probability with Venus is 6.2×10^{9} yr^{-1}, which is 1.45 times the mean collision probability of Earth-crossing asteroids with Earth [1]. Hence, the collision rate of asteroids on Venus is 0.59 x 1.45 = 0.86 times the collision rate on Earth. The collision rate per unit area on Venus is $0.86 \times 0.509 \times 10^{9}$ $km^2/0.460 \times 10^{9}$ km^2 = 0.95 times the rate per unit area on Earth.

The cratering efficiency (for sufficiently large asteroids) is somewhat higher on Venus than on Earth, owing partly to the higher rms impact speed of the asteroids and partly to the slightly lower surface gravity on Venus. If we neglect atmospheric retardation, the average cratering efficiency is 1.14 times higher on Venus than on Earth (as measured by relative crater diameters). This is equivalent to a correction to the cratering rate of $(1.14)^{2.27}$ = 1.34 relative to the cratering rate on Earth. Hence, the nominal asteroid impact cratering rate on Venus is 0.95 x 1.34 = 1.27 times the asteroid cratering rate on Earth. Before accounting for losses, we add about 10% to the total asteroid cratering rate for the undiscovered Venus-crossing asteroids whose orbits lie entirely inside the orbit of Earth and remain undetected in the conventional search programs. Thus, the total (uncorrected) asteroid cratering rate on Venus is 1.1 x 1.29 = 1.4 times the rate on Earth.

Two corrections should be considered for asteroids impacting on Venus. First, extinct comets probably should be eliminated. The ratio of extinct comets among Earth-crossing asteroids is very uncertain. No known Earth crossers are D-type objects, but there is good presumptive evidence that a few dark asteroids (F-type and C-type) are extinct comets (e.g., Phaethon, the source of the Geminid meteors, and 1986 JK, which appears cometary from its radar properties). We estimate that about 10% of the Venus-crossing asteroids are extinct comets that won't survive atmospheric passage (unless they are very large--10 km diameter or greater). This reduces the cratering rate relative to Earth to about 1.27.

Secondly, a rough correction for atmospheric deceleration of projectiles can be made as follows. Nominally, a 20-km-diameter crater on Venus is produced by an S-type asteroid 1.71 km in diameter. At an average entry angle of 45°, this body sweeps out a mass of atmosphere equivalent to about 92 kg cm^{-2}/sin 45° = 130 kg cm^{-2}. The longitudinal mass at the stagnation point of a nominal S-type asteroid is 1.71×10^{5} cm x 2.4 gm cm^{-3} = 410 kg cm^{-2}. From conservation of momentum, the impact speed ν_i will be $\nu_i = \nu_o \times 410/(410 + 130) = 0.76\,\nu_o$, and the cratering efficiency will be only $(0.76)^{2/3.4}$ = 0.85 times the efficiency for the uncorrected velocity. The cratering rate will be reduced by the factor $(0.85)^{2.27}$ = 0.69. About 40% of the craters are produced by S-type asteroids and the other 60% produced by C-type asteroids, which are larger but have lower density than S-type [1]. At the same kinetic energy, the longitudinal mass of C-types is the same as S-types and the correction for momentum transfer is the same. For crater production at 20-km diameter, the asteroid cratering rate on Venus is 0.69 x 1.27 = 0.88 times the rate on Earth. With increasing crater diameter, the relative rate increases; at 50-km crater diameter, the relative rate on Venus is 0.84 x 1.27 = 1.06 times the rate on Earth. For craters ≥ 20 km diameter, our best estimate of the asteroid impact cratering rate is $(3.7 \pm 2.0) \times 10^{-15}$ km^{-2} yr^{-1} on Earth [1] and $(3.3 \pm 1.8) \times 10^{-15}$ km^{-2} yr^{-1} on Venus.

All except a few of the largest impact craters on Venus probably have been produced by asteroids, as the atmosphere tends to shield the surface from impact of comets. Applying our estimate of the crater production rate, we find an average crater retention age at 20 km crater diameter of 260 + 310, - 90 million years for the Venusian surface imaged by the Venera spacecraft [2] and 240 + 290, - 85 million years for the portion of the surface imaged by the Magellan spacecraft [3].

References: [1] Shoemaker, E.M., Wolfe, R.F., and Shoemaker, C.S., 1990, in Sharpton, V.L., and Ward, P.D., eds., Geol. Soc. America Spec. Paper 247, p. 155-170. [2] Schaber, G.G., Shoemaker, E.M., and Kozak, R.C., 1987, Solar System Research, v. 21, p. 89-93. [3] Schaber, and 7 others, 1991, this volume. [4] Veeder amd 5 others, 1989, Astron. Jour., v. 97, p. 1211-1219. [5] Williams, J.G., 1969, Ph.D. Thesis, Univ. Calif. at Los Angeles, 270 p. [6] Shoemaker, E.M., Williams, J.G., Helin, E.F., and Wolfe, R.F., 1979, in Gehrels, T., ed. Asteroids: Tucson, Univ. Ariz. Press, p. 253-282. [7] Opik, E.J., 1951, Proc. Roy. Irish Acad., v. 54A, p. 168-199.

TABLE 1. VENUS-CROSSING ASTEROIDS: MAGNITUDES, DIAMETERS CROSSING DEPTHS, AND COLLISION PARAMETERS

	H	Diam km	q AU	Depth AU	a AU	e	i deg	dr/dt AU/10^4yr	Tc 10^4yr	Ps 1/10^9yr	Po 1/10^9yr	vi km/s
VENAPOL ASTEROIDS												
3200 Phaethon	14.65	6.9	(0.14)	-----	1.271	(0.89)	(22)	-----	-----	-----	(2.2)	(41)
1566 Icarus	16.45	0.9	0.198	0.596	1.078	0.816	15.0	1.9	5.32	2.3	3.9	36.0
2212 Hephaistos	14.0	~5	0.239	0.653	2.163	0.890	8.74	25	0.83	0.62	2.1	38.3
1990 UO	20.5	~0.2	0.265	0.485	1.234	0.785	21.0	2.1	4.79	1.2	2.4	34.9
1989 VA	17.0	~1	(0.29)	-----	0.728	(0.60)	(29)	-----	-----	-----	(4.8)	(29)
3838 1986 WA	15.5	~3	0.381	0.302	1.505	0.747	24.7	1.9	4.11	0.77	1.6	32.6
1990 SM	16.5	~2	0.393	0.452	2.157	0.818	10.7	11	1.06	0.62	1.9	31.4
2100 Ra-Shalom	16.12	2.4	0.402	0.448	0.832	0.516	8.76	0.38	9.20	8.6	11	22.3
2340 Hathor	20.2	(0.2)	0.403	0.387	0.844	0.523	5.19	0.42	8.48	13	16	22.1
3753 1986 TO	15.0	~3	0.412	0.374	0.998	0.587	15.8	0.57	7.53	3.2	4.7	25.6
1974 MA	14.0	~5	(0.42)	-----	1.775	(0.76)	(38)	-----	-----	-----	(1.0)	(36)
1984 KB	16.4	1.4	0.429	0.485	2.221	0.807	3.27	14	0.76	1.7	4.2	29.2
5025 P-L	15.9	~2	(0.44)	-----	(4.2)	(0.90)	(6.2)	-----	-----	-----	(1.1)	(31)
1864 Daedalus	15.02	(3.1)	0.451	0.216	1.461	0.691	20.1	1.3	3.91	1.2	2.1	28.6
1954 XA	18.9	~0.5	0.471	0.368	0.777	0.394	4.41	0.21	10.9	23	23	17.8
3362 Khufu	18.15	0.7	0.479	0.302	0.990	0.516	7.76	0.44	7.36	7.2	9.3	21.4
2201 Oljato	15.56	1.4	0.511	0.382	2.174	0.765	1.38	7.4	0.89	3.8	6.0	25.4
2101 Adonis	18.2	~1	0.513	0.345	1.875	0.727	2.09	3.4	1.58	4.8	6.9	24.6
1865 Cerberus	16.91	1.0	0.522	0.226	1.080	0.517	14.4	0.40	6.81	4.0	5.1	22.0
1990 MU	15.0	~3	0.543	0.202	1.622	0.665	29.4	-----	-----	-----	2.4	29.2
4450 1987 SY	17.20	~1	0.555	0.247	1.442	0.615	1.97	0.94	3.35	11	11	21.1
1989 PB	17.2	~1	0.567	0.201	1.063	0.467	9.62	0.31	6.86	7.0	8.1	19.0
1979 XB	19.0	~0.5	0.586	0.286	2.264	0.741	12.0	3.27	0.99	1.2	2.0	23.4
4183 1959 LM	14.60	~4	0.594	0.152	1.981	0.700	10.2	-----	-----	-----	1.8	22.2
4341 1987 KF	15.70	~3	0.597	0.237	1.837	0.675	6.80	1.4	1.84	3.3	4.4	21.0
1983 TF2	17.5	~1	0.605	0.140	2.439	0.752	16.4	-----	-----	-----	0.60	24.1
4034 1986 PA	18.20	1	0.608	0.160	1.060	0.426	10.3	0.22	7.10	8.4	8.8	17.6
1981 Midas	16.9	~1	(0.62)	-----	1.776	(0.65)	(40)	-----	-----	-----	(1.5)	(32)
1937 UB	17.0	~1	0.627	0.185	1.639	0.617	6.67	0.70	2.58	5.4	6.0	19.1
1990 BG	14.0	~5	0.634	0.126	1.486	0.573	32.2	0.11	4.81	6.2	2.4	27.5
1989 QF	17.0	~1	0.640	0.142	1.155	0.445	5.73	0.22	5.88	14	14	16.1
1989 UQ	19.0	~0.5	0.643	0.132	0.915	0.297	1.94	0.12	8.97	59	42	13.7
1862 Apollo	16.23	1.4	0.652	0.147	1.471	0.557	7.38	0.36	3.44	8.0	7.5	17.5
1987 OA	18.5	~1	0.658	0.140	1.490	0.558	13.5	0.26	3.50	6.2	4.7	18.8
1988 EG	18.0	~1	0.665	0.124	1.270	0.476	3.14	0.22	4.81	24	19	15.4
3554 Amun	15.94	2.0	0.672	0.074	0.974	0.310	22.7	-----	-----	-----	3.7	19.6
1990 VA	20.0	~0.3	0.679	0.090	0.984	0.310	14.2	0.07	8.56	16	13	15.8
1990 TG1	15.0	~3	0.681	0.286	2.486	0.726	8.63	1.4	0.55	4.8	3.5	18.5
4581 1989 FC	20.60	~0.2	0.681	0.095	1.023	0.334	4.79	0.10	7.16	35	30	13.5
3360 1981 VA	16.55	1.8	0.684	0.061	2.462	0.722	24.7	-----	-----	-----	1.7	24.3
1989 UR	18.0	~1	0.688	0.085	1.080	0.363	12.8	0.08	7.22	16	13	15.6
2063 Bacchus	17.6	~1	0.694	0.052	1.078	0.356	10.1	-----	-----	-----	13	14.7
VENAMOR ASTEROIDS												
1990 HA	17.0	~1	0.426	0.320	2.567	0.834	4.10	-----	-----	-----	1.5	30.1
1989 DA	18.0	~1	0.427	0.320	2.166	0.803	6.12	-----	-----	-----	1.6	29.4
4197 1982 TA	15.40	1.8	0.450	0.296	2.297	0.804	13.7	-----	-----	-----	0.88	29.5
3288 Seleucus	15.34	2.8	0.685	0.061	2.032	0.663	4.73	-----	-----	-----	0.68	17.0
1990 UA	19.5	~0.4	0.688	0.058	1.721	0.600	1.30	-----	-----	-----	8.1	15.9
1990 UQ	17.5	~1	0.691	0.054	1.571	0.560	4.52	-----	-----	-----	4.0	15.6
1990 UN	23.5	~0.05	0.692	0.054	1.709	0.595	3.00	-----	-----	-----	3.2	15.7
1988 VP4	15.5	~3	0.692	0.054	2.263	0.694	12.9	-----	-----	-----	0.77	18.9
1983 LC	19.0	~0.5	0.694	0.053	2.629	0.736	1.11	-----	-----	-----	1.2	17.0
1988 XB	17.5	~1	0.717	0.029	1.467	0.511	5.32	-----	-----	-----	4.0	14.1
1988 TA	21.0	~0.2	0.717	0.030	1.541	0.535	4.63	-----	-----	-----	3.5	14.2
1980 WF	18.5	0.6	0.721	0.026	2.231	0.677	5.07	-----	-----	-----	0.43	15.4
2329 Orthos	15.1	~3	0.726	0.019	2.404	0.698	20.1	-----	-----	-----	0.52	21.2
1978 CA	17.8	1.9	0.727	0.019	1.125	0.354	26.6	-----	-----	-----	0.45	21.5
2062 Aten	16.96	0.9	0.739	0.007	0.966	0.235	19.2	-----	-----	-----	0.71	16.8
6743 P-L	17.3	~1	0.740	0.007	1.681	0.560	8.89	-----	-----	-----	0.16	15.3
1950 DA	15.8	~2	0.742	0.003	1.683	0.559	13.4	-----	-----	-----	0.07	16.7
1983 VA	16.5	~2	(0.81)	-----	-----	-----	-----	Chaotic orbit			-----	-----
1973 NA	15.5	~3	(0.88)	-----	-----	-----	-----	-----	-----	-----	-----	-----
1986 JK	19.0	~1	(0.90)	-----	-----	-----	-----	5:2 Commensurability			-----	-----
3752 Camillo	15.6	~2	(0.98)	-----	-----	-----	-----	-----	-----	-----	-----	-----
2608 Seneca	17.57	0.9	(1.03)	-----	-----	-----	-----	3:1 Commensurability			-----	-----
1915 Quetzalcoatl	18.97	0.3	(1.08)	-----	-----	-----	-----	3:1 Commensurability			-----	-----

Note:

Within each class (Venapols and Venamors), asteroids are listed in order of increasing perihelion distance: estimated perihelion at the time of Venus crossing is used to order all asteroids with formally derived crossing depths. Other asteroids are listed in order of current perihelion distance.

H is absolute magnitude in the V band, as determined from observation by internationally adopted formulae.

The column headed Diam gives the estimated diameter in kilometers. Accurately determined diameters, based on infrared observations, have been taken chiefly from [4]. Diameters estimated from accurate magnitudes, where albedos have been assumed on the basis of spectrophotometric classification, are shown in parentheses. Approximate diameters, where magnitudes are based on photographic observations and spectrophotometric class is unknown, are preceded by symbol ~.

Perihelion distance, q, is at the time of Venus crossing, except for values in parentheses, which are osculating perihelion distances.

Depth is the crossing depth (the maximum overlap of the orbit of the asteroid with the orbit of Venus along the radius to the node) determined from the theory of Williams [5].

The orbital elements a (semimajor axis), e (eccentricity), and i (inclination with respect to the invariable plane) and the derivative of the radius to the node, dr/dt, are estimated representative values at the time of Venus crossing. Tc is the period of precession of the major axis with respect to the line of the nodes in the invariable plane. Ps is the probability of collision with Venus calculated from the equations of Shoemaker et al. [6], and Po is probability of collision with Venus calculated from the equations of Opik [7]. Uncertain values are shown in parentheses.

The column headed vi gives the impact speed in kilometers per second, corresponding to the orbital elements shown for the time of collision with Venus. Collision is assumed to occur at 0.723 AU for Venapols and at 0.746 AU for Venamors.