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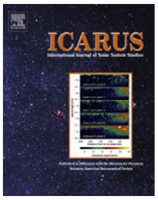

Dynamical and collisional evolution of Halley-type comets

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ABSTRACT

The number of observed Halley-type comets is hundreds of times less than predicted by models (Levison, H.F., Dones, L., Duncan, M.J. [2001]. Astron. J. 121, 2253–2267). In this paper we investigate the impact of collisions with planetesimals on the evolution of Halley-type comets. First we compute the dynamical evolution of a sub-set of 21 comets using the MERCURY integrator package over 100 Myr. The dynamical lifetime is determined to be of the order of 10^5–10^6 years in agreement with previous work. The collisional probability of Halley-type comets colliding with known asteroids, a simulated population of Kuiper-belt objects, and planets, is calculated using a modified, Öpik-based collision code. Our results show that the catastrophic disruption of the cometary nucleus has a very low probability of occurring, and disruption through cumulative minor impacts is concluded to be negligible. The dust mantle formed from ejected material falling back to the comet's surface is calculated to be less than a few centimeters thick, which is insignificant compared to the mantle formed by volatile depletion, while planetary encounters were found to be a negligible disruption mechanism.

1. Introduction

It is well established that comets on orbits with periods $P < 200$ years evolve physically. Their orbital periods are short enough that frequent passages through the inner Solar System will cause changes in the structure of the comet. These changes result from collisions and different physical processes such as sublimation, thermal stresses and the formation of an insulating dust mantle on the comet. Observations of comets show that dust mantles are a common feature, and that in such cases activity emanates from a small area in the nucleus, as observed on Comet 1P/Halley (Keller, 2005). The presence of such localized activity is supported by the rapid and strong variation of cometary activity as a function of nucleus rotation (e.g. from the Deep Impact approach to Comet Tempel 1 (Farnham et al., 2007)).

Halley-type comets are considered to evolve from the near-parabolic flux, where perturbations by the giant planets result in the dynamical transfer of comets onto short-period orbits. However, as investigated by Emel'yanenko and Bailey (1998), the number of observed Halley-type comets is hundreds of times less than predicted. The discrepancy can be accounted for by the existence of a large population of dormant Halley-type comets. However, this explanation is contradicted by the work of Levison et al. (2001). They assume a constant influx into the inner Solar System of approximately 12 comets per year from the Oort cloud, following Wiegert and Tremaine (1999). Levison et al. (2001) found that only approximately 1% of the expected observed comets have been observed. They concluded that ~99% must physically disrupt before becoming dormant. While no known disruption mechanisms are expected to explain the missing comets, no quantitative data is available on the effect of collisional disruption. This paper investigates collisional disruption mechanisms to ascertain if they can account for the missing comets.

A possible disruption mechanism is through collisions with planetesimals; a collision with a large planetesimal may result in the fragmentation of the comet if the energy produced is greater than the binding energy that holds the comet together. For example, a collision of a large asteroid, e.g. 100 m in diameter with a 10 km comet would have catastrophic consequences for the comet (Section 6.1). Collisions with smaller planetesimals may directly remove mass from the comet. For 9P/Tempel 1, this mass loss has been calculated by Yamamoto et al. (2010) to be $\sim 2 \times 10^5$ kg yr^{-1}. This is several orders of magnitude lower than the mass loss through water sublimation of $\sim 6 \times 10^9$ kg yr^{-1} observed by Schleicher et al. (2006). This small number does not necessarily imply that minor collisions do not influence comets in general. 9P/Tempel 1 is a Jupiter family comet, not a Halley type comet, and since collisions are greatly influenced by orbital characteristics, a larger sample is required to estimate the effect on the cometary population. Collisions with smaller planetesimals may also result in the temporary and localized reactivation of the cometary nucleus as has been observed on main-belt comets. These comets, which reside in the main asteroid belt, only periodically show a cometary dust tail, which is considered to result from ice being uncovered by minor impacts (Hsieh and

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Jewitt, 2006; Haghighipour, 2010; Jewitt et al., 2010; Snodgrass et al., 2010).

Additionally, cometary nuclei can be disrupted and/or removed by directly impacting planets and the Sun, or as a result of intersecting a planet's Roche radius. An impressive example of such an event occurred when Comet Shoemaker-Levy 9 (D/1993 F2) intersected Jupiter's Roche radius splitting the comet up into at least 21 discernible fragments. The splitting of the cometary nucleus is not necessarily catastrophic, resulting in total disruption, it can also refer to the removal of small fragments (e.g. Boehnhardt, 2004). In general splitting has the effect of increasing activity or reactivating the cometary nucleus.

This paper investigates the dynamical and collisional interactions of Halley-type comets with the two main groups of planetesimals, asteroids in the main asteroid belt and Kuiper belt objects, and splitting due to planetary encounters. First, in Section 2, the orbits of 21 representative Halley-type comets are dynamically integrated over 100 Myr. In Section 3, the sizes and orbital parameters of planetesimals is the Solar System are discussed. Then in Section 4 the collisional probability is calculated using an Öpik-based collision code. At every point in the orbital evolution, the collisional probability is computed and is used to calculate the collision probability with a population of asteroids and Kuiper belt objects. In Section 5, the evolution of the collision probability is correlated with the dynamical evolution. The physical disruption and mantle formation that result from collisions will be discussed in Section 6.

2. Dynamical evolution

2.1. Distribution of comets

'The Catalogue of Cometary Orbits (Marsden and Williams, 2008) lists 67 Halley-type comets. In this paper, Halley-type comets are defined as comets with a period $P < 200$ yr and a Tisserand parameter with respect to Jupiter $T < 2$. In order to investigate the collisional evolution of Halley-type comets, 21 comets have been selected based on inclination following Bailey and Emel'yanenko (1996). The initial parameters of the selected comets are listed in Table 1. Variational orbits or clones, of the comets were generated by changes of order 10^{-6} in the semi-major axis (a). The initial cometary orbits are labelled as <name>_ 00, with the suffix 00 becoming p1, p2, m1 or m2 for the clones with plus or minus the small variations. These results should be interpreted statistically as they are long-term integrations of 'test' objects with initial orbital elements close to, or the same as, the observed Halley-type comets.

2.2. Integrations

The MERCURY integrator package of Chambers (1999) was used to integrate the orbital elements of 21 Halley-type comets. The RADAU integrator option from Everhart (1985) was primarily selected, which uses weighted step sizes and variable Gauss–Radau spacing. This method is widely established for orbital integrations including close approaches. In the MERCURY implementation of RADAU, unnecessary errors are minimized by the selection of a suitable order in which the step sizes are added together.

The integration spanned over a period of 10^8 years, with an orbital elements evaluation every 10,000 years. The RADAU accuracy parameter was set to 10^{-10}. Comets were regarded as being ejected when reaching heliocentric distance of 2000 AU. All eight planets were included, with the Earth–Moon system treated as one body. For this analysis the cometary orbits were integrated backwards in time. As noted by Levison and Duncan (1994), there is no statistical significance in whether the integration is carried out forwards or backwards in time, and either can be viewed as examples of the future behavior of the system.

2.3. Evolution of Halley-type comets

The orbits of Halley-type comets are intrinsically chaotic. During their dynamical lifetimes, there are many opportunities for the comets to be ejected onto hyperbolic orbits, or for the comet's perihelion distance to evolve down to a sun-grazing or a sun-colliding end state (see Bailey et al., 1992). As discussed by Bailey and Emel'yanenko (1996), ejection onto a hyperbolic orbit (or ejection from the system) can have three causes: (i) direct ejection due to a close encounter with a planet; (ii) gradual chaotic evolution of the semi-major axis as a result of secular and mean-motion resonances; and (iii) ejection as a result of a small perturbation during a period of small perihelion distance. The final state and time of the initial 105 cometary clones (including the initial cometary orbits) are plotted in Fig. 1. During the integration, 85 are ejected and 20 become sun-colliding or sun-grazing.

To illustrate the typical dynamical evolution, four Halley-type comets have been plotted in Figs. 2 and 3. These are considered

Table 1
Initial orbits and sizes of the 21 comets used in this work. Sizes marked * are measurements from Lamy et al. (2004). The other sizes have been randomly assigned using the size distribution described in Section 3.1. These sizes are required for the collisional calculations in Section 4.

Name		d (km)	a (AU)	e	i (°)	ω (°)	Ω (°)	M_0 (°)	Epoch (days)
1P	Halley	11*	17.92010	0.967267	162.1960	112.4496	59.5078	65.8502	2448440.5
12P	Pons–Brooks	1.50	16.99378	0.954092	74.8211	199.0073	256.1434	235.1583	2420080.5
13P	Olbers	2.34	16.69026	0.929009	44.7212	64.1079	86.4850	230.8354	2429480.5
20D	Westphal	7.81	15.71375	0.921784	40.9827	56.5824	348.3078	138.5152	2451612.5
23P	Brorson–Metcalf	2.97	16.91486	0.972323	19.3553	129.4891	311.5833	53.3216	2452240.5
27P	Crommelin	1.95	9.10121	0.918950	29.2365	195.8923	250.9757	208.2919	2452280.5
35P	Herschel–Rigollet	1.50	28.55724	0.974549	65.0302	29.0410	356.5060	142.2692	2452800.5
55P	Tempel–Tuttle	3.6*	10.33037	0.905362	162.4890	172.5188	235.2656	19.9486	2453654.5
109P	Swift–Tuttle	26*	26.34252	0.963162	113.3406	153.2379	139.5132	18.7760	2388520.5
177P	Barnard 2	2.07	23.86577	0.954243	31.1685	60.4912	272.3414	339.4528	2435640.5
1827M1	Pons–Gambart	1.50	14.70790	0.944259	136.6244	19.8374	320.6184	13.2165	2444320.5
1984A1	Bradfield 1	2.49	27.29090	0.949792	51.6972	219.1357	356.7136	40.5110	2445680.5
1989A3	Bradfield 2	1.92	18.79406	0.977508	82.3324	194.7642	28.3616	48.9666	2445760.5
1991L3	Levy 1	11.6*	13.83064	0.929324	19.1664	41.5035	329.4167	59.2973	2446480.5
1998G1	LINEAR 1	4.23	12.07494	0.823270	109.6993	236.3556	341.3955	9.6393	2447800.5
2000D2	LINEAR 14	5.54	17.29255	0.867131	156.9918	117.6794	235.8874	359.0734	2448960.5
2000G2	LINEAR 13	2.36	14.22367	0.809000	170.4791	101.7514	328.3862	359.3356	2450120.5
2001Q6	NEAT 6	1.73	7.99521	0.823656	56.8525	43.2722	22.1547	330.4169	2450520.5
2001W2	BATTERS	1.79	17.87078	0.941149	115.8765	142.0711	113.3336	350.5659	2450880.5
2002CE10	LINEAR 34	1.60	9.82501	0.791355	145.4105	126.0747	147.3583	319.4019	2451120.5
2005T4	SWAN	2.99	9.28032	0.929103	160.0437	41.3506	25.3641	286.3421	2451580.5