ASTEROID SATELLITES FORMED BY TIDAL DISRUPTION

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ABSTRACT

Results from simulations of the tidal disruption of km-sized gravitational aggregates are presented. In many cases the post-encounter remnants form binaries that are stable for at least 60 d. The physical and orbital properties of these binaries vary over a wide range and show that tidal disruption can lead to the formation of double asteroids with spheroidal or ellipsoidal components of near-equal mass. Systems with large mass ratios are also readily formed. Orbital eccentricities as low as 0.09 were seen, suggesting many systems could be stable over very long time periods.

1. INTRODUCTION

Recent observations of asteroids have revealed the existence of satellites among the near-Earth and main-belt populations (see [1] for a review). Favorable suggested methods of satellite formation include: 1) tidal splitting during a close encounter with a planet; and 2) formation via collision either by retention in orbit of post-collision ejecta around the largest remnant or by mutual capture of escaping fragments [2]. Direct numerical simulations that include both collisional physics and gravity are just now beginning to explore these possibilities [3,4].

Previous work on tidal splitting either used an idealized two-particle model of the progenitor or were designed to explore issues other than satellite formation [5,6]. In the present study, results from simulations of the tidal disruption of km-sized gravitational aggregates by the Earth show in unprecedented detail the formation of binaries with a wide range of physical and orbital properties.

2. METHOD

The numerical simulations were carried out using `pkdgrav`, a parallel treecode that accounts for interparticle gravity and collisions [7]. Each simulated scenario consisted of sending a rubble-pile asteroid made up of ~ 1000 identical smooth spherical particles on a hyperbolic flyby of the Earth. The tidal field of the Earth (modeled as a point potential) pulls the asteroid apart until the field weakens sufficiently for the asteroid fragments to collapse back on themselves due to their own self-gravity. Typically the excess angular momentum delivered by the planet prevents the asteroid from recollapsing into a single body. Instead the collapse results in smaller clumps, some of which may enter into mutual orbit. The aim of the present study is to determine the variety of final configurations that contain mutually orbiting fragments.

Thirty-two simulations with different close-approach distances q and encounter velocities v_∞ were performed. In each case the asteroid progenitor had a bulk density of 2 g cm^{-3}, dimensions of $4 \times 2 \times 2$ km, and a 6 h prograde spin. Note that the shape of the asteroid can affect the encounter outcome depending on the exact orientation at periapse (see [6] for details). The coefficient of restitution for collisions was set to 0.8. A fixed timestep of ~ 50 s was used for the integrations, which typically ran for ~ 10 d of simulated time. Mutually bound fragments were identified at the end of each run using a fast satellite detection algorithm called `companion` [8]. For the present study, only those bound pairs whose primary was at least 10% of the total system mass and whose secondary was at least a few percent of the mass of the primary were considered. Computed quantities included the semi-major axis a of the pair, the eccentricity e, the mass ratio μ, the spin period of the primary P_1 and secondary P_2, the ellipticity ϵ_1, ϵ_2 of each component (computed as $\epsilon = 1 - \frac{1}{2}(a_2 + a_3)/a_1$, where $a_1 \geq a_2 \geq a_3$ are the semi-axes of the body), and the orbital time τ.

Some runs were extended to 60 d of simulated time using a new feature of `pkdgrav` that allows a rubble pile to be "frozen" into a rigid body, eliminating the costly interparticle collision calculations that otherwise do not contribute meaningfully to the dynamics. This is valid so long as the two orbiting components do not approach one another too far inside a mutual

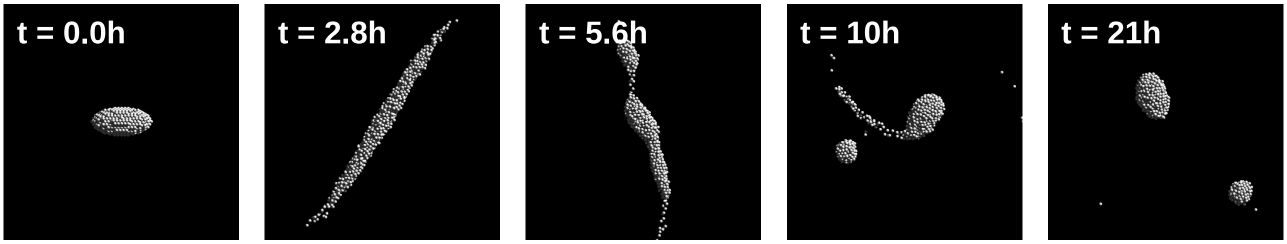

Figure 1. Snapshots of the tidal breakup of an asteroid passing by Earth with q = 1.6 km and v_∞ = 6 km s^{-1}.

Roche radius (roughly two primary radii). The rigid-body equations of motion with torque (see [9], Eqs. 4 and 6) were solved using a 4th-order Runge-Kutta with timestep equal to the `pkdgrav` step (which was never larger than 1% of the mean spin period of either body).

3. RESULTS

For the simulations in this study, q ranged from 1.2 to 2.0 $R_\oplus$, where $R_\oplus$ is the Earth's radius, and v_∞ ranged from 3 to 18 km s^{-1}. Since maximum stress is at periapse and drops off rapidly with distance, the start point was set quite close to the planet (at a distance of $2q$) and the starting speed and direction of motion were computed accordingly. For reference, the Roche limit was 3.47 $R_\oplus$ for these simulations.

Table 1 summarizes the results for those simulations that satisfied the mass criteria outlined in the previous section. Usually the satellite systems consisted of the first- and second-largest post-encounter remnants, but in one case the secondary was the third-largest remnant. Also note that one system was actually a triple (with $a = 10$ km, $e = 0.12$, and $\mu = 0.21$ with respect to the primary), though it would not likely have survived long as such. The systems that were run for 60 d are indicated with an asterix ($\star$). Typically these were quite stable, with the mean a and e changing only by a few percent, usually to higher values. This sort of evolution in a is consistent with spin-orbit coupling between the bodies since the shorter spin periods of the bodies compared to their orbital period leads to mutual torquing that pushes the bodies apart (the spins change as well). The growth of e is less well understood and in general can be difficult to predict [10,11].

Fig.1 shows snapshots of one of the simulations (q = 1.6 km, v_∞ = 6 km s^{-1}) for illustration. The long-term behavior of this system is plotted in Fig.2. The spikes in the plot correspond to periapse passages. The longer-scale osciallation indicates strong coupling between the bodies due to their non-spherical shapes. Integration over longer timescales would require a more careful monitoring of energy conservation due to the dissipative nature of the Runge-Kutta algorithm.

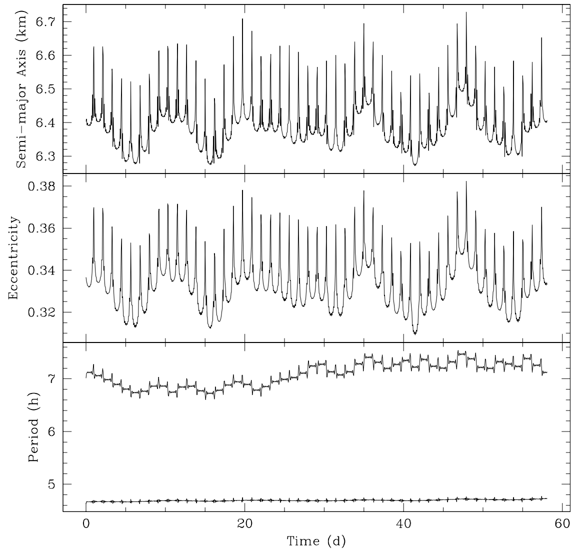

Figure 2. Evolution of a (top panel), e (middle panel), P_1 (bottom panel, lower line), and P_2 (bottom panel, upper line) for 60 d following the breakup of the asteroid illustrated in Fig.1.

4. CONCLUSIONS

The wide variety of possible outcomes from tidal disruption of gravitational aggregates, even from the relatively sparse sampling of this study, is evident in Table 1. Among the binaries, a ranged from 3.3 to 30 km, e from 0.09 to 0.93, μ from 0.03 to 0.91, spin periods from 4.2 to 15.1 h, ellipticities from 0.03 to 0.65, and τ from 0.6 to 12.7 d. It is therefore possible to obtain "double" asteroids, where the components are roughly the same mass, and more traditional parent-satellite systems, where the satellite is small compared to the parent, by the same mechanism of tidal disruption with only a small change in the encounter parameters.

In future work, the secular evolution of these systems, including their long-term stability, will be assessed. The numerical results will be compared with analytic constraints to investigate the rate of energy dissipation in the evolving system and to understand the transfer of angular momentum and energy between the rotational and translational states of the system. A larger database of tidal encounters

Table 1. Summary of satellite systems. See text for explanation of symbols.

q ($R_\oplus$)	v_∞ (km s^{-1})	a (km)	e	μ	P_1	P_2	ϵ_1	ϵ_2	τ (d)	Notes
1.20	12.0	13.6	0.93	0.80	5.7	8.6	0.17	0.03	4.0	
1.20	15.0	14.1	0.81	0.15	4.7	5.1	0.43	0.15	3.7	
1.50	6.0	29.6	0.89	0.69	4.4	4.7	0.42	0.27	12.7	
1.50	7.0	5.9	0.49	0.43	7.6	5.8	0.18	0.16	1.1	triple system
1.55	5.5	3.3	0.16	0.16	4.7	15.1	0.19	0.08	0.6	secondary is 3rd largest
1.55	6.0	6.8	0.09	0.54	4.6	5.3	0.45	0.21	1.3	$\star$
1.55	6.5	7.3	0.24	0.51	4.8	11.1	0.26	0.04	1.4	$\star$
1.60	5.0	8.7	0.31	0.76	4.4	4.8	0.44	0.52	1.9	$\star$
1.60	5.5	6.5	0.23	0.91	4.6	4.2	0.22	0.28	1.2	$\star$
1.60	6.0	6.4	0.34	0.30	4.6	7.0	0.38	0.19	1.2	$\star$
1.70	5.0	15.7	0.67	0.03	5.1	6.2	0.65	0.17	4.5	$\star$

will be constructed for comparison with observations and will include an assessment of outcome probabilities. For example, it may be possible to distinguish between collisional and tidal origin for satellites by comparing numerical simulations with observations of satellites (including their debiased frequency of occurence) in the near-Earth versus the main-belt population. With a larger parameter search it may also be possible to discover asteroids that are slowly rotating or tumbling, either as a direct result of the tidal breakup or through repeated encounters with a companion. This may help shed light on the origin of these strange rotators that appear to make up a disproportionate part of the population of asteroids with measured spins.

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