IMPACT EJECTA ROTATIONAL BURSTING AS A MECHANISM FOR PRODUCING STABLE IDA–DACTYL SYSTEMS

Ian Giblin[1], **Jean-Marc Petit**[2] **and Paolo Farinella**[3]

1. Gruppo di Meccanica Spaziale, Dipartimento di Matematica,
Università di Pisa, Via Buonarroti 2, I–56127 Pisa, Italy
E–mail: ian@brl.u–net.com

2. Observatoire de la Côte d'Azur,
B.P. 4229, F–06304 Nice Cedex 04, France
E–mail: petit@obs–nice.fr

3. Gruppo di Meccanica Spaziale, Dipartimento di Matematica,
Università di Pisa, Via Buonarroti 2, I–56127 Pisa, Italy
E–mail: paolof@dm.unipi.it

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Send editorial communications to:
Paolo Farinella
Dipartimento di Matematica, Università di Pisa
Via F. Buonarroti 2
I–56127 Pisa, Italy
E–mail paolof@dm.unipi.it
Tel. +39–50–844254, Fax +39–50–844224

Abstract. The existence of Dactyl, the small satellite of asteroid 243 Ida, presents an intriguing paradox: if exposed to the same projectile bombardment as Ida, it should have been disrupted long ago. To solve this paradox, it has been proposed that either Ida (and the entire Koronis family) is relatively young (≈ 100 Myr), or Dactyl has reaccreted many times from its own debris after having been disrupted. Here we propose a third alternative, that is that Dactyl is much younger than Ida, and it was formed by rotational bursting of a precursor fragment ejected from Ida after an impact. We discuss some recent experimental results showing that sizable fragments from shattered targets do undergo rotational bursting and are fissioned after traveling over a length of several target diameters; the relative speed between the fission remnants is comparable to the initial ejection velocity. Then we have performed a number of numerical integrations of the orbits of fictitious particles resulting from an assumed rotational bursting event in the gravitational field of Ida; the results show that, depending on the initial conditions, up to several percent of the particles get trapped into stable satellite–like orbits resembling that of Dactyl. We conclude that this mechanism may have formed Dactyl in the last $\approx 10\%$ of Ida's lifetime, either after an energetic cratering impact or (more probably) after a collision which shattered Ida without dispersing most of its fragments "to infinity".

1. Introduction

After the discovery of the satellite Dactyl of asteroid 243 Ida by the *Galileo* spacecraft, studies of asteroidal satellites have been moved from the realm of speculation into one based on the comparison between models and actual data. It has been noted soon that the small size of Dactyl (mean diameter about 1.4 km) and the heavily cratered surface of Ida, which according to most collisional models implies an age of 1–2 Byr for this asteroid (Chapman et al. 1995, Davis et al. 1996) are at odds with the idea that Ida and Dactyl were formed together during the breakup event generating the Koronis asteroid family (Durda 1996). The reason is that the same collisional flux impinging on Ida should have shattered Dactyl within a few hundred Myr since its formation (Geissler et al. 1996). Therefore, the contemporaneous formation scenario appears to require that either Dactyl has been shattered and reaccreted many times since the formation of the system, or Ida is much younger than 1 Byr. The former idea has been suggested by Davis et al. (1996) and the latter by Greenberg et al. (1996), but both raise major problems, as discussed in those papers.

An alternative is that Dactyl was not formed at the same time as was Ida and the Koronis family. Weidenschilling et al. (1989) suggested that small asteroidal satellites might be formed from accretion of orbiting ejecta. In this scenario, a fraction of the ejecta from a large cratering impact would stay into orbit, perhaps as a result of gravitational perturbations from the spinning, triaxial primary and of mutual collisions. Davis et al. (1996) estimated that a few percent of the ejecta from a large crater on Ida would be sufficient to form Dactyl. On the other hand, numerical simulations of the orbital evolution of bodies launched from Ida's surface (Geissler et al. 1996) have shown that the vast majority of them reimpact Ida after a comparatively short time (of the order of one day)), and that indeed this process accounts well for the distribution of large solid blocks visible on the surface (Lee et al. 1996). Therefore, any nongravitational process which could raise the periapse of an ejected fragment and prevent it from reimpacting would need to act very quickly. No quantitatively convincing model for such a process has been envisaged yet.

Here, we intend to discuss a variant of this scenario which may prove to be relevant for the formation of Dactyl. The basic idea is that a rapidly spinning ejected fragment may undergo rotational bursting a short time after ejection, and that as a result of this process the outward trajectory of at least one of the fissioned bodies could be modified in such a way as to have it

inserted into a stable satellite–like orbit.

From the physical point of view, it is clear that in the absence of self–gravitation, any rotating body will be in a state of tension. If the body is sufficiently weak it may break apart, with the two or more resulting bodies (through conservation of momentum) acquiring opposing changes in velocity. Typically this phenomenon would be expected to occur very soon after the formation of a weak fragment in a breakup event and for this reason would not necessarily be observable in laboratory experiments. Fujiwara and Tsukamoto (1980) mentioned briefly the issue of rotational bursting, stating that *"Generally, no collisions among fragments occurred, but in the exceptional case some spinning fragments were split into smaller ones and collided with other fragments"*. During a detailed study of a total of 420 fragments across 4 experimental shots, Giblin *et al.* (1994a) found several candidate cases of rotational bursting, but no definitive evidence for the occurrence of this process. On the other hand, a thorough analysis of new experimental data has convinced us that the bursting process is real, although for a small fraction of the fragments. Using as a benchmark the one single case of observed rotational bursting for which we have the most complete data, we will show that this process may have been responsible for the insertion of Dactyl in a stable orbit. While we recognize that only a subset of the *a priori* plausible parameter space leads to stable Dactyl–like satellites, the chance of the "right" combination of circumstances having actually occurred depends on the total number of sizable fragments ejected from Ida during its lifetime, which is not currently well known.

The remainder of this paper is organized as follows. In Section 2 we briefly describe our experimental approach and data reduction techniques, and then we discuss the results of these experiments relevant for the problems of identifying and studying rotational bursting. In Section 3 we describe and discuss a range of numerical simulations which we have performed to assess whether rotational bursting may be effective to insert Ida ejecta into stable satellite–like orbits. Finally, in Section 4 we consider the implications of this work and its relevance for the formation of the real Ida–Dactyl system.

2. Experimental technique and results

The experiments discussed here were performed in 1992 and are reported briefly in Giblin and Farinella (1997) and more thoroughly in Giblin et al. (1997). They are very similar to experiments carried out in 1989 by the same group and discussed in Giblin et al. (1994a). We

direct readers to these previous papers for details and here we report only a summary of the techniques and instrumentation.

The targets used in these experiments were 21 cm diameter spheres of "artificial rock", made using alumina cement, carborundum (SiC_2) and water in the correct stoichiometric ratio for this type of cement. This composition makes the material harder than most granites, but softer than basalt. The density of the cured cement was 1.77 g/cm^3 and the static compressive strength 1.7×10^4 J/kg (comparable to values derived for "weak" natural rocks, see e.g. Takagi et al. 1984). No harder cores were present in any of the 1992 experiments but of the 4 targets considered here, 2 contained fabrication–stage fractures in the form of spherical sections centered on the impact point. The motivation for including these fractures was to investigate the possible change in outcome when an impact is made into a contact binary or a prefractured body.

The targets were placed on a 70×70 cm steel table 2 cm thick, which had a central hole of diameter 5 cm, and were "impacted" from below by exploding a contact charge. This technique involves filling a small cylindrical cavity in the target with plastic explosive, which is then detonated electrically. The explosive used was Gelatine 2b, which has a detonation velocity of 6.1 km/s, density 1.42 g/cm^3 and specific energy 4.44×10^6 J/kg. We refer to Giblin et al. (1994b) for a detailed discussion of the explosive technique to simulate hypervelocity impacts.

Whilst the outcome of a low–velocity (hundreds of m/s) impact depends critically on the mechanical properties of the target and impactor, this is not the case for high–velocity (km/s) impacts, where the outcome is primarily a function of delivered specific energy. In our case, the value of the critical specific energy, E/M (where E is the kinetic energy of the equivalent projectile, and M is the mass of the target), was of the order 10^7 erg/g. This is approximately the value required to achieve catastrophic fragmentation of rocky materials through hypervelocity impacts carried out at laboratory scales (Fujiwara et al. 1989).

The experiments were filmed using three cameras — one fast–shuttered CCD video camera and two high–speed NAC E–10 cine cameras. The cine cameras, running at a nominal 400 frames/sec, were at a mutual angle of 60° and the sides of the resulting equilateral triangle (camera, camera, target) measured 12 m. The 16 mm cine film from these experiments was subsequently transcribed to PAL VHS video cassette, then digitised frame–by–frame using an Acorn RiscPC computer system. The resulting image set, consisting of 800 frames from each high–speed camera, was analysed using a specially developed software. The capabilities of the software are substantial and have allowed a very detailed analysis to be carried out. This is a

major factor in our being able to identify and study unusual events such as fragment splitting.

Fragments were initially tracked using the mouse; we recorded a few positions in each view for all the visible fragments. Where a fragment was travelling across the plane of view, only a minimum of user input was required to correctly measure the trajectory. The computer then interpolates to fill the intervening frames. In the case of fragments moving significantly toward or away from the camera, the trajectory is geometrically more complex and simple linear or quadratic interpolation does not work; in these cases more points were recorded by hand. Once this is done, we can call up an animated display where the fragment is cut from each image and replayed centrally on the screen as if stationary. From this animated display, where the two views of a possibly matched fragment are displayed side by side, it is usually straightforward to measure fragment spin rates and shapes, as well as match fragments between the two views. It is in this context that unusual fragment behaviour is most apparent.

Let us now describe the results of these experiments which are most relevant in the current context. In the four well–analysed impact experiments from the 1992 series, a total of 528 fragments were identified and tracked in the first camera sequences, with a further 289 tracks recorded for the second camera. We cannot say with any certainty how many of these fragments were actually "overlapping" (i.e., tracked in both views) – less than 100 have so far been identified in 3D and matched between the views. Therefore for the purposes of this discussion we will consider only camera 1 data.

Of the 528 fragments identified and studied in camera 1 of our 1992 experimental films, only *one* fragment was seen to indisputably undergo rotational bursting. Nevertheless this event did occur at some distance from the target and provides a worthwhile study in itself. Figure 1 shows frame 116 of the high–speed film sequence from each camera. Note that the fragment was ejected toward the cameras, between the two. This has the effect that it moves to the right in the left hand view, but to the left in the right hand view. The main purpose of Fig. 1 is to illustrate the distance travelled by the fragment before it broke - it travelled more than 5 target diameters before the two parts did visibly separate. The parent fragment and the larger "daughter" had longest axes of about 78 and 58 mm, respectively; we can estimate that the smaller "daughter" had a mass roughly half as big as the larger one (see Fig. 2).

The parent fragment was rotating 13 times per second before break–up and the larger remnant did not measurably change its rotational period in the bursting process. It should be noted that the larger remnant was not visible for long after breaking up and an accurate

measurement of the rotation rate is difficult. By chance, the smaller remnant remained visible for longer and has a more accurately measured rotation rate of 9.1 rots/s. The three–dimensional velocities of the large and small fragments after the separation were (within errors of ± 0.1 m/s) 4.1 and 3.1 m/s, and their relative velocity 1.1 m/s. The ejection velocity of the bursting fragment was 5.8 m/s, but the shape of the trajectory was somewhat affected by gravity as can be seen from Fig. 1 (the fragment was ejected at about 55° from the horizontal). A remarkable point here is that if the fragment trajectory had not been curved by gravity, this parent fragment would have travelled 8.0 target diameters and left the field of view *before* breaking up.

The primary fragment underwent 3.7 rotations in the 0.29 sec before it burst apart. It is not clear from the films whether the fragment was rotating simply or tumbling — if the latter, this might explain how it could survive close to 4 complete rotations and then break up, possibly as a result of varying internal stresses. Although tumbling fragments are not so rare according to Giblin and Farinella (1997), this one was not considered as such in that study.

Numerous other fragments exhibited peculiar trajectories which suggest that they may have been the result of rotational bursting (specifically, the trajectories when extrapolated backward in time were found to originate from outside the target), but none of these can yet be confirmed. It may be possible, by looking for pairs of deflected trajectories, to distinguish between rotational bursting cases and fragments which were deflected by some other mechanism. Some ejecta, initially travelling downward, were seen to hit the table and bounce back — so we cannot assume that deflected fragments are all due to bursting.

Another experimental observation is worth comment here: in recent heavy cratering (of $\approx$ 10 cm cement spheres) experiments carried out at the NASA Ames Vertical Gun Range (D. Davis, I. Giblin, M. Di Martino, paper in preparation) a small round fragment was seen to be "knocked" by a larger elongated fragment in much the same way as a baseball bat hits a ball. The smaller fragment was significantly deflected. The event occurred no more than 2 target diameters from the impact — of course, the probabilty of such a collision drops rapidly with radial distance — and we do not discuss it here beyond this mention as a curiosity. Inevitably, rotating fragments must collide like this during the initial expansion of the disrupted target, but this is the first time one such event has been clearly seen on experimental films. The data for these experiments have not been analysed in any depth — hopefully a full analysis will reveal more quantitative data and more of these surprising events. From a dynamical point of view, it is clear that fragment deflection by rotational bursting and by impact are equivalent, so the

numerical simulations described in Sec. 3 to assess the probability of obtaining stable satellite orbits from an impulsive velocity change can be seen as relevant for both scenarios.

In conclusion, while we have only one very clear observation of rotational bursting, this observation shows that this phenomenon is certainly *possible*. Given the extreme difficulty of identifying such events in experimental data, together with the unconfirmed possible bursts mentioned earlier, it seems plausible that rotational bursting may occur for a small fraction (perhaps $\approx 1\%$) of the sizable fragments from a breakup event. We have no reason to think that the same phenomenon cannot occur for fragments ejected after energetic cratering events, such as those which produced a number of large impact basins on Ida's current surface (as we shall discuss later, it is even possible that Ida has undergone one or more shattering impacts, followed by reaccumulation of a fraction of the fragments into a "rubble pile"). We shall now discuss whether as a consequence of rotational bursting some ejected fragments may remain trapped into a stable orbit around an Ida–like asteroid.

3. Numerical simulations

The simulations presented here use the same numerical approach as those reported in Petit et al. (1997). Here, we only briefly recall the main points. The central asteroid is modelled using a set of 44 packed spheres whose position and mass are chosen to represent the real shape of Ida (Thomas et al. 1996), assuming a uniform density of 2.9 g/cm^3 consistent with the results of long–term stability studies (Petit et al. 1997; note, however, that the assumed value for the density is not a crucial parameter in the current context). We integrate the equations of motion in the reference frame rotating with Ida, with the asteroid's centre at the origin, and use a Bulirsch–Stoer integrator (Stoer and Bulirsch 1980) with an accuracy control parameter set to 10^{-10}. The actual error has been estimated from the variation of the Jacobi integral, which should be conserved for a test particle orbiting an irregular body (that is, neglecting the interaction between different orbiting fragments). According to such tests, the error is less than 10^{-13} at every time step, and of the order of 10^{-9} in relative value after some 10^6 orbits.

In order to simulate the rotational bursting of a fragment ejected from Ida, we have to start from estimating its size, ejection velocity and bursting height. As for the size, we assume that Dactyl is the smaller fissioned fragment, in order to allow for a larger deflection of its velocity. Its current shape is nearly spherical, possibly resulting from "erosion" by cratering events and/or from partial reaccretion of orbiting ejecta (Geissler et al. 1996, Davis et al. 1996); if we assume

an initial fragment–like axial ratio, Dactyl's original longest axis would have been about 2 km, and assuming an hypothetical parent fragment about 3 times as massive, we end up with a parent having a longest axis of length L between 2.5 and 3 km. As for the ejection velocity V_{ej}, we assume values between 10 and 30 m/s, comparable to the escape velocity from Ida's gravitational pull. Finally, we assume that the bursting event occurs when the parent fragment reaches a given distance from the centre of Ida, comparable to the distance of Dactyl from Ida at the time of the *Galileo* observations (about 85 km). Of course, this choice maximizes the chances of producing a Dactyl–like orbit, but is also consistent with the experimental evidence, as explained below.

We note that for the bursting fragment described in Sec. 2 we have the relationship $\omega \approx V_{ej}/L$, where ω is the fragment's angular velocity of rotation. Such a relationship is expected from the semi–empirical model of breakup processes by Paolicchi et al. (1989), since ω would just be of the order of the gradient of the fragment ejection velocity field. Applying this scaling relationship to our fictitious fragments ejected at speeds between 10 and 30 m/s and using $L \approx 2.75$ km, we obtain that the corresponding rotation periods are of the order of 10^3 s. If the splitting phenomenon occurs after 4 rotations, the distance travelled by the parent fragments before they split is about $8\pi L \approx 70$ km. This is somewhat lower than the observed distance of Dactyl from Ida, but given that Dactyl's orbital elements are not well known and that we are scaling over more than four orders of magnitude in size, the agreement is quite remarkable.

As in the simulations reported by Geissler et al. (1996, Sec. 2.3), the fragments are assumed to start from the surface of Ida, with the starting site in the large impact basin Wien Regio (0°N, 8°E, near one of the "tips" of the asteroid; see Fig. 2 in Greenberg et al. 1996). The initial direction of the ejection velocity is taken either at 30° or at 60° from the local horizontal (with the azimutal angle taken at random). The fragments are assumed to split as soon as they reach a distance from the center of Ida ranging from 80 to 150 km, as discussed above. The relative velocity of the two departing fragments (with the smaller one getting 2/3 of it as a velocity increment) is assumed to range from 0.2 to 1.0 times the starting velocity, with a direction chosen in two different ways: (i) either we choose at random the direction of the spin axis, perpendicular to the initial velocity vector (in agreement with experimental results, see Giblin et al. 1997), and then the relative velocity is selected at random perpendicular to the spin axis (in order to mimic the expected behavior for a rotational bursting process); (ii) or we just choose the direction at random, from an isotropic distribution. After splitting, the 2 daughter

fragments are separated by 2 km in the direction of the relative velocity, the centre of mass of the system remaining unchanged. The 2 fragments are assumed to interact gravitationally, since their initial distance is small and their trajectories may undergo some deflection; note, however, that the mutual escape velocity is a few m/s, always less than the initial relative speed.

For every run, we have integrated the orbits of a large number of fictitious fragments, following them from their ejection until they split or collide with Ida. When splitting occurs before collision, the orbits of the two daughter fragments are followed for 10^8 s (about 3 yr). During all that time, the two fragments interact gravitationally with each other. The possible fate of a fissioned fragment is either a collision with Ida (easy to detect), or an escape (which we define as an orbit of positive energy at a distance from the centre of Ida greater than 500 km), or a stable satellite–like orbit. Note that perturbations due to solar gravity can be neglected over time spans as short as those covered by our integrations; even on much longer time scales, they do not affect significantly the stability of this type of orbits, well inside Ida's gravitational sphere of influence (Chauvineau and Mignard 1990, Petit et al. 1997).

Figs. 3, 4 and 5 show graphically the results of 90 such simulations, all of them with 1000 initial particles. In the figures, we show how many among the smaller daughter fragments are found on a stable orbit at the end of the 10^8 s integration time, versus the ratio between the fission–related separation velocity and the ejection velocity V_{ej}. In Figs. 3a–c, we compare the results corresponding to different splitting distances (ranging from 80 to 150 km) for three values of the ejection velocity ($V_{ej} = 10$, 15 and 20 m/s). Figs. 4a–c show the effect of the orientation of the fission–related velocity increment: isotropical (solid line) versus perpendicular to the spin axis (long–dashed line). Finally, in Figs. 5a–c, we illustrate the effect of the orientation of the initial ejection velocity vector: 60° (solid line) versus 30° (dashed line) from the horizontal.

From the inspection of these results, some trends are apparent. The most important parameter is certainly the ratio between the velocity increment related to the splitting event and the ejection velocity from Ida (provided the latter exceeds a minimum threshold ≈ 10 m/s). In order to get a significant fraction of satellite–like orbits (typically, several percent), the separation velocity must be at least about half of the ejection speed. The orientation of the of the fission–related velocity increment (isotropical vs. perpendicular to the assumed spin axis of the parent object) does not appear to play an important role (see Fig. 4). On the other hand, the orientation of the ejection velocity vector (30° vs. 60° from the horizontal) does affect the results, especially for large ejection velocities (Fig. 5) and for small splitting distances.

We have performed some more simulations whose results are not shown in the Figures. For instance, lower splitting distances typically yield fewer satellites; for splitting distances of about 50 km satellite orbits are possible only provided the ratio between the separation and ejection velocities approaches unity. Also, we have tested what happens when we change the starting site on Ida: the only significant change in the results is that we have to somewhat rescale the initial velocities taking into account the variable local escape velocities and rotational speeds (since we chose a position near one of Ida's "tips", on average similar results would be obtained with slighly higher launch speeds). In summary: the rotational bursting phenomenon definitely *can* produce Dactyl–like fragment orbits, although this occurs in a relatively small fraction of cases, which depends sensitively on some (but not all) of the input parameters of the model.

For some of the particles that are still in orbit after 3 yr, we have continued the integration over a time span 10 times longer, and checked the evolution of the orbital parameters. In the cases corresponding to a splitting distance between 80 and 100 km, about half of the surviving orbits turn out to be stable on the longer time span. They all have an eccentricity less than 0.6 and a semimajor axis in the range from 75 to 200 km. Actually, among all the particles satisfying the previous conditions, only a few turn out to be unstable, owing either to a rather high inclination (exceeding 30–40° and reaching, in a few cases, even retrograde–orbit values), or to small inital pericentre distances (less than 68 km). For high–inclination orbits, the chaotic zone associated with the mean motion resonances becomes quite large (Petit and Lemaitre 1997), so it is likely that all orbits with inclinations $\gtrsim 60°$ are unstable on the long term.

The situation is different in the case when the splitting event is assumed to occur at 150 km altitude. Between 80% and 90% of the surviving orbits seem to be stable over 30 yr, even though the semimajor axis can reach several hundred km, and the eccentricity 0.8. It turns out that all these orbits have a pericentre distance $\gtrsim 100$ km, which make them stable on that time scale, whereas in the previous case the pericentre distance could not be larger than the splitting distance, between 80 and 100 km. It is clear that a larger splitting/pericentre distance increases the number of stable fragments, but then one would need some dissipative mechanism to lower the orbit, since Dactyl was observed at about 85 km from the centre of Ida.

4. Conclusions

We have shown that rotational bursting occurs after breakup events (Sec. 2) and that it can result into stable, satellite–like orbits of some fragments (Sec. 3). However, estimating the

chance that this explanation applies to the real Dactyl is another story. If Dactyl's collisional lifetime is only a few hundred Myr (Geissler et al. 1996, Davis et al. 1996) and Ida (with the rest of the Koronis family) is really much older than that, we should estimate the probability of forming one Dactyl–like satellite over the last 10 or 20% of Ida's lifetime.

The results reported earlier in this paper suggest that at most a few percent of the sizable fragments from a breakup event undergo rotational bursting, and in a few percent of these cases a stable satellite may be the outcome: overall, this would amount to about one satellite over 1000 fragments a few km in size. Since 1000 such fragments have about the same mass as the current Ida, it seems unlikely (although not impossible) that Dactyl results from one impact crater formed in the last 10–20% of Ida's lifetime. A more likely alternative is that Ida has been shattered several times during its lifetime, but has reaccumulated into a "pile of rubble" as a consequence of an energy gap between the smallest shattering impact and the energy required to disperse most fragments to "infinity" against their mutual gravitational pull (this possibility has been discussed in detail by Davis et al. 1996). Possibly during the last such event, some 10^8 yr ago, at least one of the ejected fragments underwent the bursting process and the surviving Dactyl is the result.

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Figure captions

Fig. 1. Frame 116 (corresponding to 0.29 seconds after the impact) from each of the high–speed cameras. The angle between the cameras is 60°. Also indicated are the target size and position, fragment trajectory in each view and a box showing the first visible separation of the two splitting fragments.

Fig. 2. A sequence of frame cut–outs from the right hand camera, tracking the parent fragment and the largest remnant. Inspection of frames 080–110 confirm that no other fragment is approaching the parent and that the bursting is not ambiguous. The solid grey area visible in the final three frames indicates the edge of the image.

Fig. 3. Number of fragments remaining stable for at least 3 years vs. the ratio between separation and ejection velocities, for different splitting distances: 80 km (solid line); 90 km (long–dashed line); 100 km (short–dashed line); 150 km (dotted line). The initial velocity is taken at 60° from the local horizontal, and the velocity increment at bursting is distributed isotropically. (a) $V_{ej} = 10$ m/s, (b) $V_{ej} = 15$ m/s, and (c) $V_{ej} = 20$ m/s.

Fig. 4. Number of fragments remaining stable for at least 3 years vs. the ratio between separation and ejection velocities, for isotropically distributed velocity increments (solid line) and for velocity increments perpendicular to the assumed spin axis (long–dashed line). The initial velocity is taken at 60° from the local horizontal, and $V_{ej} = 20$ m/s. (a) Splitting distance 80 km, (b) splitting distance 90 km, and (c) splitting distance 100 km.

Fig. 5. Number of fragments remaining stable for at least 3 years vs. the ratio between separation and ejection velocities, for initial velocities at 60° (solid line) and 30° (long–dashed line) from the local horizontal. Splitting is assumed to occur at a 90 km distance, and the corresponding velocity increment to be distributed isotropically. (a) $V_{ej} = 10$ m/s, (b) $V_{ej} = 15$ m/s, and (c) $V_{ej} = 20$ m/s.

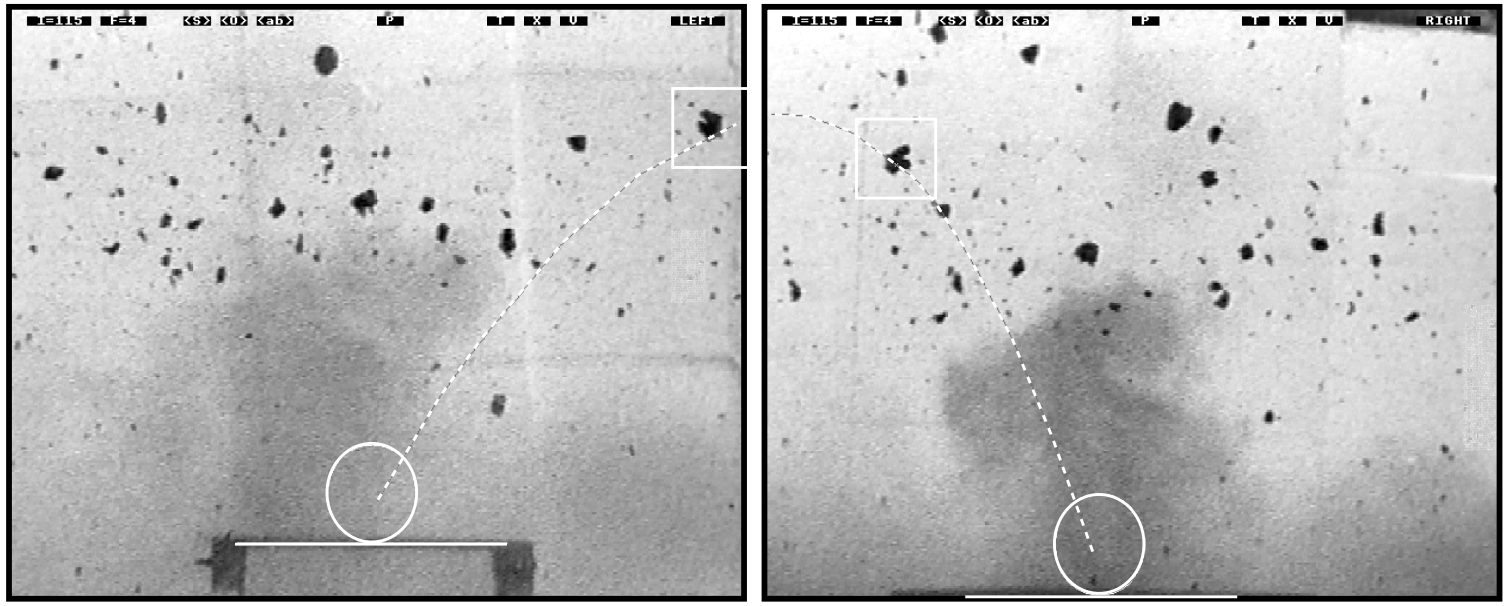


Figure 1

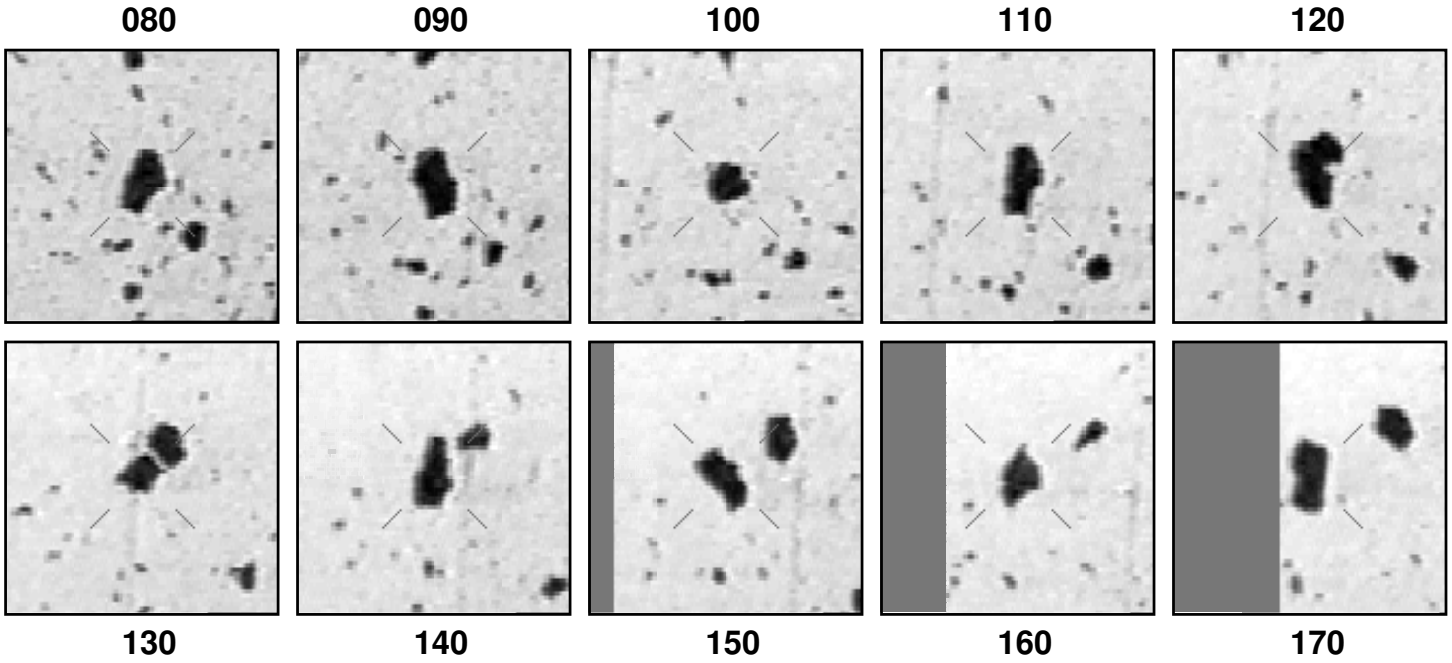
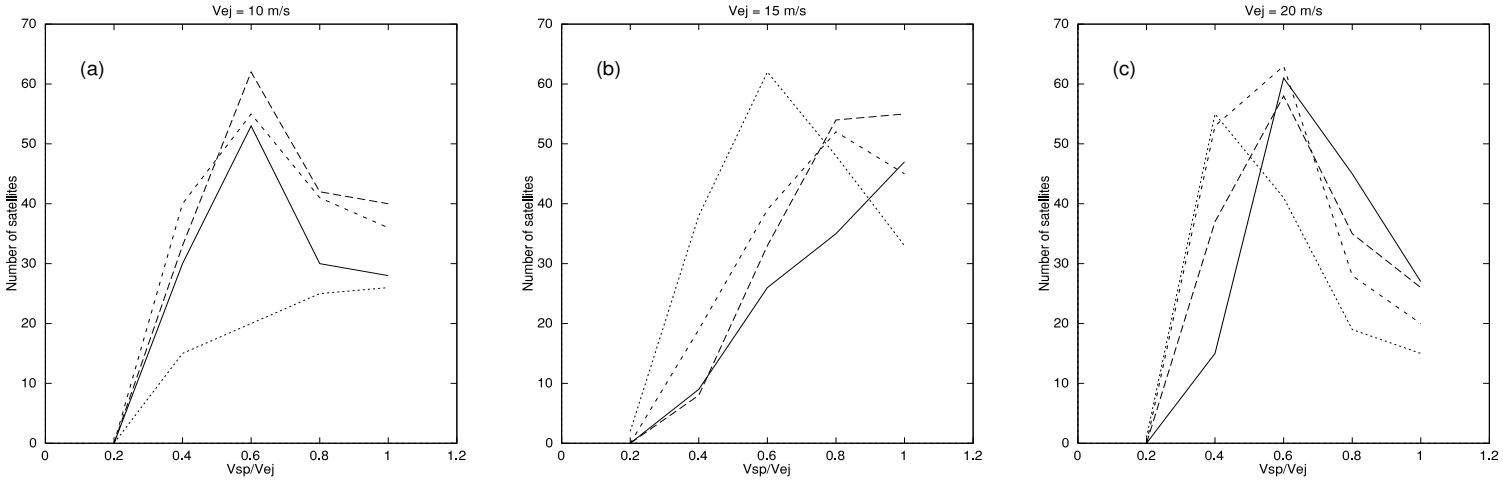
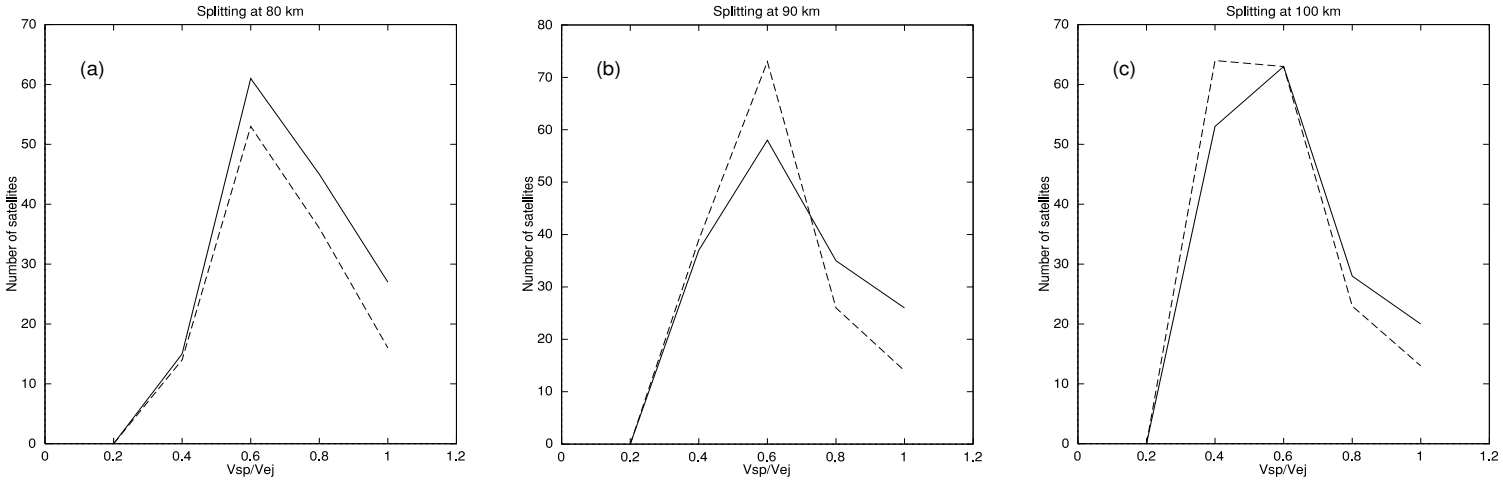
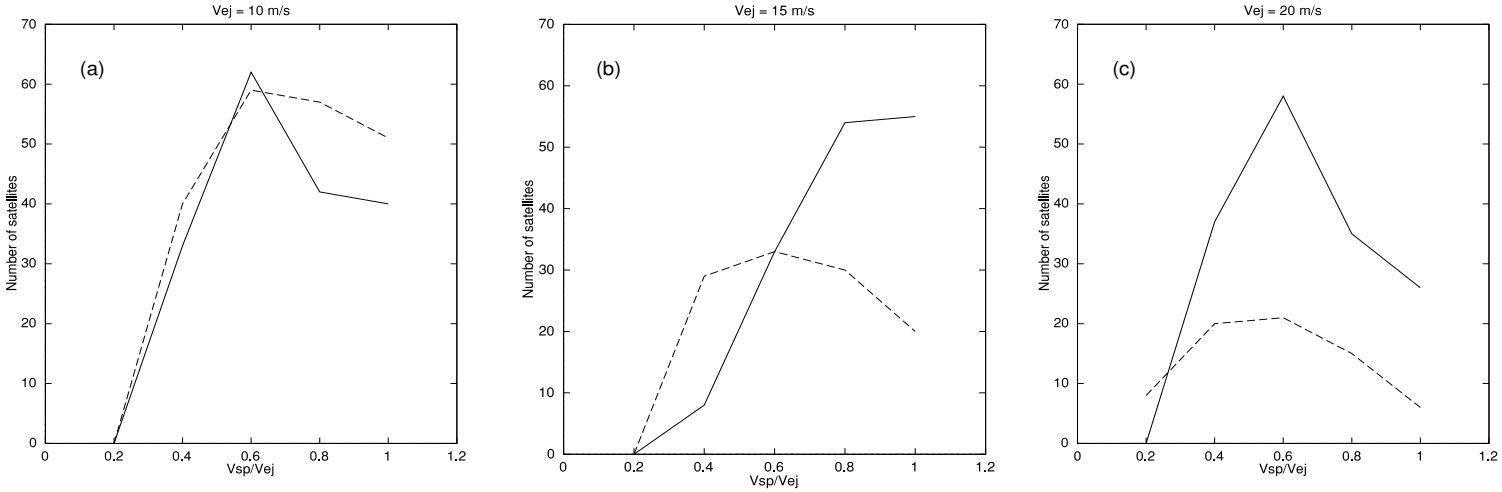


Figure 2


Vej = 10 m/s
(a)
Number of satellites
Vsp/Vej
Vej = 15 m/s
(b)
Number of satellites
Vsp/Vej
Vej = 20 m/s
(c)
Number of satellites
Vsp/Vej


Splitting at 80 km
(a)
Number of satellites
Vsp/Vej
Splitting at 90 km
(b)
Number of satellites
Vsp/Vej
Splitting at 100 km
(c)
Number of satellites
Vsp/Vej


Vej = 10 m/s
(a)
Number of satellites
Vsp/Vej
Vej = 15 m/s
(b)
Number of satellites
Vsp/Vej
Vej = 20 m/s
(c)
Number of satellites
Vsp/Vej