the case if the escaping photons share the average energy of the emitting particles, such as in multiple Compton scattering[12–14]. To constrain further the radiation mechanism[12] equation (1) must be combined with detailed time-domain information and a model for the origin of the spectral break[13,14].

Combining equations (1) and (2) we have

$$\Phi_0 = Nf/\Omega d^2 \tag{3}$$

where $f = \langle E\rangle/\langle v\rangle$ is a constant of the order of unity. For those bursts in which Φ_0 is invariant for repeating pulses as in Fig. 3, equation (3) implies that those pulses retain the same number of emitting particles, hinting that they originate from the same burst site and that the plasma is confined. This would favour astrophysical models in which the different pulses are produced by a regenerative source rather than a single catastrophic event[15]. Though the above interpretation is independent of the specific radiation mechanism, it suggests that the spectral softening and pulse-decay timescale[16] are controlled by the radiative cooling process and not by the energy supply. Independent of its interpretation, equation (1), if confirmed by data with higher time-resolution, should greatly influence astrophysical modelling of GRBs. ☐

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Formation of asteroid satellites and doublet craters by planetary tidal forces

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APPROXIMATELY ten per cent of the impact structures on the Earth and Venus are doublets[1,2]—pairs of craters formed by the near-simultaneous impact of asteroids of comparable size. It has been suggested that these doublet craters form from asteroid fragments dispersed by aerodynamic forces during atmospheric entry[1,3], or from asteroids that were tidally disrupted by gravitational forces shortly before impact[4–6]. But to form a doublet, the progenitors of the craters must have been well separated before final impact[1], which poses problems for both mechanisms. Here we argue that a hitherto undetected population of well separated binary asteroids can explain the occurrence of doublet craters. By modelling asteroids as weak, gravitationally bound aggregates ('rubble piles'), we show that the tidal forces experienced during close encounters with the Earth can generate binary asteroids, in a process similar to that which fragmented the comet Shoemaker–Levy 9 (ref. 7) as it passed by Jupiter. Although the resulting binary asteroids may eventually separate or coalesce before colliding with a planet, repeated close encounters with the Earth maintain a steady-state population that is sufficiently large to explain the observed number of doublet craters.

At least 3 of the 28 largest impact structures on Earth with diameters greater than 20 km have a nearby companion crater sharing the same formation age[1]. Among the other terrestrial planets, only Venus has been surveyed quantitatively for doublet craters[2]. Crater pairs on Venus are identified by their close association and/or by morphology indicating simultaneous formation (that is, shared ejecta blankets and crater walls, with no overlapping features). Results from these surveys show that Venus's observed doublet-crater population fraction is smaller than Earth's (only 2–3%), though one must take account of Venus's thick atmosphere which shields its surface from small impactors. If Earth's atmosphere were as thick as Venus's, only one of its three doublet craters would have been formed, making its proportion of doublets essentially the same as Venus's. In addition, by surveying the fraction of doublet 'splotches', radar-dark features created by projectiles so small (< 200 m) that they catastrophically disrupt in Venus's atmosphere, we find a representation of Venus's impactor population ($\sim 14\%$) which is consistent with Earth's fraction of doublet craters ($\sim 10\%$).

We suggest that asteroid satellites, generated as a by-product of close encounters between asteroids and planets, can produce the fraction of doublet craters observed on Earth and Venus. To quantify this hypothesis numerically, we model close encounters between loosely bound contact-binary asteroids and the Earth using an adaptive fifth-order Runge-Kutta numerical integrator[1,8]. For each test case, we use a Monte Carlo method, starting with 10,000 contact-binary asteroids initially far from the Earth with randomly chosen initial orientations, a selected encounter velocity V_∞, and a selected close approach distance d (Fig. 1). These objects are assumed to be initially in mutual contact but co-orbiting each another, and so have periods of the order of 4 hours. Our results show that contact-binaries can be tidally perturbed into co-orbiting asteroids, though the separation distance between the components is almost always too small to produce a doublet crater (that is, in most cases, the separation distance is only a few times the mean diameter of the original asteroid).

To first order, our results agree with the limited outcome statistics of more sophisticated (and time consuming) N-body codes treating encounters between rubble-pile asteroids and the Earth (ref. 9 and D. R. Richardson, personal communication). Rubble-pile asteroids are defined as a collection of gravitationally self-bound components ranging in size from micrometres up to 100 m or kilometre-sized fragments (that is, they are not dust piles). Similar to contact-binaries, rubble-piles undergo 'mass-stripping', implying that only small ($\sim$ 100-m) individual fragments are created or ejected, or 'tidal fission', implying similar-sized components were created, during close Earth encounters if they have one (or more) of the following characteristics: (1) a fast prograde rotation rate (near the critical breakup limit), (2) an elongated shape (mass is more readily shed from the ends of the asteroid), (3) periapse distance close to Earth, (4) low encounter velocities, and/or (5) low bulk density. Moreover, if more than two fragments are stripped from a rubble-pile, the multiple-fragment system evolves into a binary system where the extra fragments either collide with a bound fragment or escape[10]. Thus, because fragment clusters should evolve similarly to star clusters, where the most stable end-states are binary systems, both models yield similar orbiting outcome results.

Once the asteroid's components are orbiting one another, they become susceptible to further small perturbations during repeated distant Earth encounters and mutual tidal forces which modify their mutual separation distance. To model these effects, we combined our numerical model of planetary encounters (described above) with another Monte Carlo code[11] that computes the frequency and characteristics of repeated multiple encounters with Earth along with mutual tidal effects between the components. The Monte Carlo code uses a probability distribution for asteroid velocities at encounter based on actual orbits of Earth-crossing asteroids[12]. Our results show that if an asteroid satellite is formed during a close approach with Earth, distant perturbations often substantially increase the separation distance between the components in a random-walk fashion; components can also escape or collide with one another. Tidal forces between the components can also increase (or decrease) the separation distance, though their effect decreases substantially when the components are far apart.

Even though the scheme we have modelled produces a large number of well separated binary asteroids, we find that most of these binary asteroids do not survive to strike the Earth; close approaches with Earth, which are more probable than impact encounters, nearly always cause the binary's components to escape one another. Thus, if contact-binary asteroids only produce a single satellite from planetary tidal forces, few (if any) doublet craters would be formed. Even an initial population of binary asteroids from the main asteroid belt would not enhance the observed fraction of doublet craters on Earth because most secondary components would be lost before impact.

However, rubble-pile asteroids have the potential to produce an asteroid satellite each time they have a close encounter with the Earth, conceivably replacing any satellite lost during a previous (or the same) encounter. As long as these rubble piles maintain sufficient mass, mass-stripping of small components off the primary or even tidal fission may occur many times over their lifetime. But these secondary components, if small enough, would probably be unable to produce a doublet crater on Venus (or even the Earth) because atmospheric screening would prevent them from striking the surface. This screening process prevents the formation of craters caused by satellites smaller than ~100 m diameter on Earth or 1 km on Venus.

Using this concept of continuous rebirth of secondary satellites during close encounters, we can determine the steady-state distribution of binary asteroids in the Earth-crossing region (Fig. 2). We find that a population of weakly bound single asteroids evolves into a population where over half (~ 57%) the objects are binary asteroids, some separated by large distances which are only limited by solar tides (solar tides cause the dispersion of components with radii of 0.5 and 1.0 km separated by more than ~60

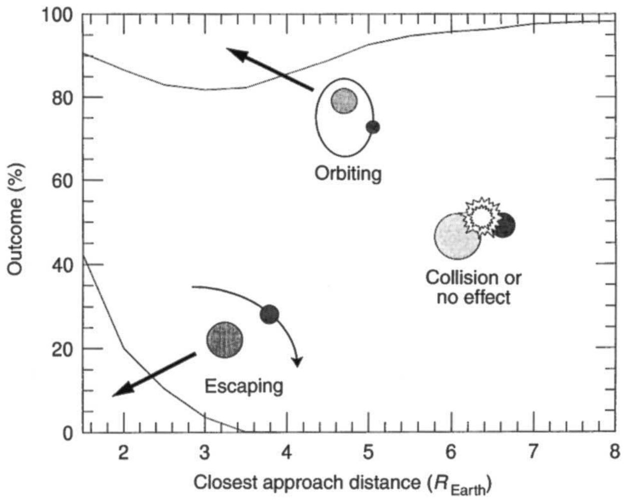

FIG. 1 Post-encounter statistics for spherical contact-binary asteroids (0.5 and 1 km in radius with a rotation period of 3.55 hours and a density of 2,600 kg m^{-3}) encountering the Earth at velocity $V_\infty = 12\,\text{km s}^{-1}$ over various closest-approach distances (*d* between 1.5 and 8.0 Earth radii, in increments of 0.5 Earth radii). Over 10,000 random initial orientations were used for each choice of V_∞ *and d*. The motion starts and finishes at a distance of 60 Earth radii. (The V_∞ value of 12 km s^{-1} represents the average encounter velocity between the Earth-crossing asteroids and the Earth[12].) The three encounter outcomes, (1) components escaping one another, (2) components colliding with one another or no effect from planetary tides, and (3) components orbiting one another, were tabulated and plotted (against *d*) as a percentage, where all the outcomes added together equal 100%. As *d* increases, the fraction of escape outcomes decreases, demonstrating that planetary tides weaken as the asteroids move away from the planet (the planetary tides decrease as $1/d^3$). The fraction of orbiting outcomes increases and then decreases as *d* increases, showing a maximum near $d = 3.0$–3.5 Earth radii where escape outcomes become extremely unlikely. The median semimajor axis between the components for each set of orbiting outcomes at a given distance *d* is 3.4 km or smaller while the median eccentricities are 0.50 or smaller, making the separation distance between the components too small to produce a doublet crater except under exceptional conditions.

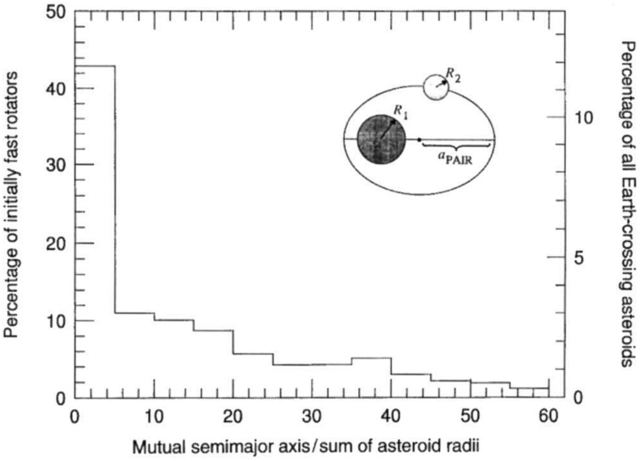

FIG. 2 The steady-state distribution of co-orbiting asteroids in the Earth-crossing region is found by allowing spherical contact-binary asteroids (0.5 and 1 km in radius with a rotation period of 3.55 hours and a density of 2,600 kg m^{-3}) to evolve over multiple encounters with the Earth using a probability distribution of relative encounter velocities V_∞ (2.0–38 km s^{-1} in increments of 4 km s^{-1})[12]. At least 90 bodies were run in the Monte Carlo code for each velocity increment. Each asteroid can evolve for as long as 100 Myr, the typical lifetime of Earth-crossing asteroids (ECAs) against planetary collision[12], though many do not survive that long. If a close Earth encounter produces a co-orbiting asteroid, distant Earth encounters then modify the newly formed binary asteroid's mutual semimajor axis, eccentricity and inclination. In the interim between Earth encounters, mutual tidal forces between the components often modify the binary's semimajor axis, eccentricity and rotation period of the larger component by exchanging rotational and orbital angular momentum[11]. The ordinate on the left-hand side of the plot shows the percentage of objects starting with this 3.55-hour rotation period that evolve into binary asteroids; the abscissa shows their mutual semimajor axis (a_{PAIR}) in units of the sum of the radii of the components ($R_1 + R_2$). Our results show that our starting asteroid population evolves into a population where over half are binaries, some separated by large distances. The mutual eccentricities of those binaries tend to be small (most orbit each other on nearly circular orbits). The ordinate on the right-hand side of the plot shows the percentage of the kilometre-sized ECAs that should have satellites (~ 15%). We obtain this percentage by scaling our results by the actual fraction of ECAs with short rotation periods (~ 28% with rotation periods < 5.5 hours; see text for details).

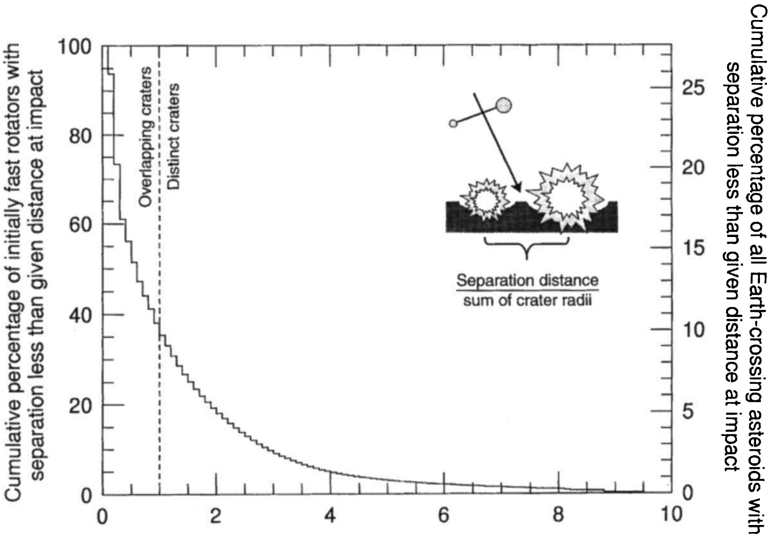

FIG. 3 The fraction of Earth-crossing asteroids (ECAs) striking Earth that produce doublet craters, calculated by putting the results of Fig. 2 into a model which numerically integrates impact encounters between binary asteroids and the Earth[1]. Encounter velocities V_∞ and other asteroid parameters are the same as described in Fig. 2. The abscissa shows the separation distance between binary asteroid components at impact divided by the sum of the crater radii found using crater scaling-law results[16,17]; a value greater than one means that the binary creates a doublet crater, and a value less than one means that the craters overlap one another. The ordinate on the left-hand side of the plot shows the cumulative percentage of objects with 3.55-hour rotation periods that strike Earth at a given separation distance or smaller. The ordinate on the right-hand side of the plot shows the cumulative number of kilometre-sized ECAs that strike Earth at a given separation distance or smaller. Our results show that $\sim$ 10% of the ECAs striking the Earth produce doublet craters.

mean diameters at 1.0 AU). But these results only take into account rapidly rotating asteroids near the theoretical breakup limit; many Earth-crossing asteroids (ECAs) are slow rotators with rotation periods longer than $\sim$ 6 hours, making them difficult to pull apart by Earth's tidal forces. To find the fraction with short rotation periods, we modelled the rotation-period distribution of the ECAs as a maxwellian distribution with a mean period of 6 hours, scaling the distribution for extremely slow rotators like 4179 Toutatis ($\sim$ 20% of the ECA population) and the paucity of rotation periods lower than 3.55 hours (ref. 13 and A. W. Harris, personal communication). It is even possible that tidal forces themselves may be the source of rapid rotation: tidal torques imparted to rubble-pile asteroids frequently increase their rotation rate, such that multiple planetary encounters may serve to spin up the body to near-disruption (A. W. Harris, personal communication). Thus, the same tidal process that disrupts critically spinning bodies may be responsible for bringing bodies to near-critical spin rates. A thorough analysis of this effect is beyond the scope of this Letter.

Our results show that $\sim$ 28% of the ECAs have rotation periods < 5.5 hours. Thus, by scaling the fraction of binary asteroids produced by our model ($\sim$ 57%) by the fraction of rapidly rotating asteroids in the ECA population ($\sim$ 28%), we can conclude that $\sim$ 15% of all kilometre-sized Earth-crossers capable of producing binary asteroids should have satellites generated by Earth's tidal forces, and this steady-state ECA population describes the population that strikes Earth.

To determine the fraction of this population forming doublet craters on Earth, we modelled impact encounters between binary asteroids and the Earth, again using an adaptive fifth-order Runge-Kutta numerical integrator[8] which accounts for Earth's tidal forces, the asteroids' encounter and impact velocities, and the trajectory and orientation of the components at impact[1]. We discovered that, contrary to earlier speculation and intuition, planetary tides just before impact decrease (on average) the distance between components at impact. Although the differential gravitational pull of the Earth during final approach increases the distance between the components, the increased separation is often in a direction radial to the planetary surface, such that the components tend to fall near or on top of one another. Consequently, $\sim$ 10% of the asteroids striking the Earth produce doublet craters (compared with the 15% of Earth-crossers that are well separated binaries), matching the percentage of doublet craters observed on Earth (Fig. 3).

No recent methodical survey has yet been attempted to find asteroid satellites among the Earth-crossing asteroid populations, though doublet craters, anomalous stellar occultation lightcurves, unusual asteroid lightcurves, elongated asteroids, and extremely slow asteroid rotation rates all have suggested they may be quite common[14]. Now, in the aftermath of the interaction of comet Shoemaker–Levy 9 with Jupiter and the discovery[15] of Dactyl orbiting 243 Ida (though Dactyl's small diameter and orbit around Ida, if not highly eccentric, suggests it would not create a doublet crater at impact), our results suggest that the time may be ripe for a new search. We recommend that any search for asteroid satellites places emphasis on kilometre-sized Earth-crossers with short rotation periods.

We note that 433 Eros, the target of the NEAR mission, has a short rotation period (5.27 hours) and an elongated shape, suggesting that it may have passed near enough to the Earth in the past to have produced a satellite. Although no such satellite has been reported, in spite of an intensive pre-encounter observing campaign, our model suggests at least a 50% probability of finding a small satellite in orbit around 433 Eros. ☐

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