Production of Tunguska-sized bodies by Earth’s tidal forces

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Abstract. Tidal disruption of rubble-pile bodies (stony or icy aggregates held together by self-gravity) during close Earth encounters may produce significant numbers of Tunguska-sized (50 m) fragments. Using an $N$-body simulation to model encounters between strengthless, elongated, rotating, particulate bodies and the Earth, two disruption categories were found which produce small bodies: (a) “Shoemaker–Levy–9 type” catastrophic disruptions, where the progenitor is pulled into a line of similarly sized bodies, and (b) rotational disruptions, where the progenitor is distorted and spun-up by tidal torque such that particles are ejected along the equator. These events occur frequently at low encounter velocities (i.e. low $e$ and $I$); it is predicted that Earth’s tidal forces should be effective at disrupting larger bodies into Tunguska-sized fragments in this region of phase space. By creating a map of tidal disruption outcomes for the progenitor’s encounter parameters and integrating over all possible values of those parameters, it is found that the tidal production rate of Tunguska-sized bodies (upper limit) was comparable with the main-belt injection rate of Tunguska-sized bodies into resonant orbits. It is concluded that tidal disruption plays an important role in maintaining the steady-state fraction of small Earth-crossing asteroids. © 1998 Elsevier Science Ltd. All rights reserved

1. Introduction

In 1908, a small 50 m body, possibly a carbonaceous chondrite, catastrophically disrupted 5–8 km above the Siberian wilderness in a remote area named Tunguska. The blast, equivalent to a 15–20 Mton hydrogen bomb, flattened trees over a 2000 km$^2$ area, roughly the size of New York City. Though scientists are still struggling today to understand the details of this event, it is clear that small bodies have the potential to produce significant damage to localized regions of our planet.

It is estimated that $\sim 10^7$ Tunguska-sized (and larger) asteroids are present in the Earth-crossing asteroid (ECA) population (Morrison, 1992). Combining this value with the mean lifetime of ECAs against Earth impact ($\sim 100$ Myr; Bottke et al., 1994a,b), we find the interval between Tunguska-sized impacts on Earth, on average, is 100 yr. Since humans reside on a very small fraction of the Earth’s surface, the danger of dying from the blast effects of a Tunguska-type impact is minimal. On the other hand, since many humans live near coastlines, the danger of dying from an impact-generated tsunami may be more significant (Hills, 1994). For this reason, the sources of Tunguska-sized impactors need to be better characterized.

Most Tunguska-sized ECAs are thought to originate in collisions between main-belt asteroids which deliver fragments to either the $3:1$ mean-motion resonance with Jupiter or the $v_6$ secular resonance. It is estimated that these collisions inject one Tunguska-sized body (TSB) per year into resonant orbits (Menichella et al., 1996). Once there, these bodies undergo orbital evolution which can transport them to the terrestrial planet region via chaotic increases to their eccentricity. The time for these objects to become Earth-crossing is $\sim 1$ Myr (Wisdom, 1983; Morbidelli and Moons, 1995). Those objects that have their eccentricity increased until they become Sun-grazing ($e \sim 1.0$) are defined as the “fast-track” population; those removed from resonance by perturbations from the terrestrial planets are defined as the “slow-track” population (Farinella et al., 1994; Froeschlé et al., 1995). Most Earth-crossing asteroids are on the “slow-track”. The dynamical lifetime of ECAs against planetary collision, catastrophic collision with another asteroid, or ejection by Jupiter perturbations is on the order of 10 Myr (Milani et al., 1989; Michel et al., 1996).
Using the injection rate of TSBs into resonance (one object per year) and the collision rate of TSBs on Earth (one object per 100 yr), Menichella et al. (1996) estimate that 1% of all TSBs on resonant orbits impact the Earth. To maintain a steady-state population of 10^6 TSBs, less than 10% of all the TSBs entering resonant orbits become part of the ECA population. This paradigm, however, may neglect an important source mechanism for TSBs in the ECA region. Weak ECAs should be vulnerable to disruption by tidal forces during close encounters with the Earth and other terrestrial planets. Because close planetary encounters occur more frequently than collisions, asteroidal tidal disruption may be capable of producing numerous small bodies, possibly even enhancing the population of TSBs near Earth.

To investigate the role of tidal disruption in producing TSBs, our paper uses the following format. We first review previous work on tidal disruption and the evidence that many asteroids approaching the Earth are weak (Section 2). Next, we describe a numerical model capable of simulating the tidal disruption of weak particulate asteroids encountering the Earth (Section 3). By analyzing the outcome statistics from asteroid encounters we gauge the effectiveness of disruption over a variety of encounter parameters (Section 4). Finally, we predict the relative efficiency of TSB production via tidal disruption (Section 5) and examine the observed population of Earth-crossing asteroids for evidence of tidal forces at work (Section 6).

2. Tidal disruption and rubble-pile asteroids

Tidal disruption was first investigated by Roche (1847) (see Chandrasekhar, 1969), who derived the distance (now called the Roche limit or Roche radius) at which a self-gravitating non-rotating liquid satellite on a circular orbit around a rigid spherical planet can no longer maintain an equilibrium figure:

\[ R_{\text{roche}} = 1.51 \left( \frac{M_{\text{sat}}}{\rho_{\text{sat}}} \right)^{1/3} = 2.45 R_{\text{pl}} \left( \frac{\rho_{\text{pl}}}{\rho_{\text{sat}}} \right)^{1/3} \]  

(1)

where \( M_{\text{pl}} \), \( R_{\text{pl}} \), and \( \rho_{\text{pl}} \) are the mass, radius, and density, respectively, of the planet and \( \rho_{\text{sat}} \) is the density of the satellite. Equation (1) shows that tidal forces are so weak that even objects with zero tensile strength need close encounters to disrupt. For example, a body with a density of 2 g cm\(^{-3}\) disrupts if it orbits the Earth at a distance less than 3.4 \( R_{\text{E}} \) where \( R_{\text{E}} \) is the Earth's radius. The disruption limit for a body approaching a planet on a parabolic orbit is even smaller (Sridhar and Tremaine, 1992; Asphaug and Benz, 1996):

\[ R_{\text{disrupt}} = 0.69 R_{\text{roche}}. \]  

(2)

Thus, an object with a density of 2 g cm\(^{-3}\) would only disrupt after passing within 2.4 \( R_{\text{E}} \) of the Earth. Since conventional wisdom (until recently) held that comets and asteroids had tensile strength and/or internal dissipation, many early studies reported that small bodies either cannot tidally disrupt, or disrupt only under special circumstances (Jeffreys, 1947; Opik, 1950; Sekiguchi, 1970; Aggarwal and Oberbeck, 1974; Mizuno and Boss, 1985). Related work by Dobrovolskis (1982, 1990) set strict limits on the size, strength, and material properties required to produce tidal disruption.

In the 1990s, sophisticated numerical and analytical studies investigated tidal disruption of spherical non-rotating strengthless objects (Boss et al., 1991; Sridhar and Tremaine, 1992; Asphaug and Benz, 1996; Solem and Hills, 1996). A good review of the issues involved and techniques used can be found in Asphaug and Benz (1996). These models reported that tidal disruption can occur among comets and asteroids if they are "rubble-piles," aggregates of strong component material held together by self-gravity rather than tensile strength. A growing body of evidence suggests such objects may be common:

- Opik (1966) suggested comet Ikeya Seki had a rubble-pile structure after observing it disrupt during a close encounter with the Sun. More recently, Asphaug and Benz (1994, 1996) concluded that comet Shoemaker-Levy-9 (SL9) could only have disrupted into 20 or so similar-sized fragments during a close encounter with Jupiter if the progenitor had been virtually strengthless.
- Harris (1996) showed that none of the 107 asteroids smaller than 10 km with known rotation periods rotate faster than the theoretical break-up limit for a strengthless, gravitating object. This result implies that rubble-pile composition may be common, since solid objects could theoretically rotate at nearly any speed.
- Large craters have been found on small bodies such as Ida, Gaspra, and Phobos. These craters, such as Stickney on Phobos, are formed in the "gravity scaling" regime, where the ultimate size of the crater is controlled by the target's self-gravity rather than its physical strength. Craters formed in the gravity regime require a weak or fragmented target, which can exist prior to impact or can be produced by the crater-forming impact itself (i.e., crater excavation is preceded by an advancing shock front, which shatters the material as it passes through). The size of the projectile needed to form the large crater Stickney on Phobos in the strength regime would instead disrupt Phobos (Asphaug and Melosh, 1993). Numerical hydrocode simulations of asteroid collisions suggest that small to moderately sized projectiles striking an undamaged asteroid produce highly fractured target bodies, even though larger blocks of material can remain intact (Greenberg et al., 1994, 1996; Love and Ahrens, 1996).
- Bottke and Melosh (1996a,b) showed that rapidly rotating rubble pile asteroids encountering the Earth could be split into multiple co-orbiting components by tidal forces. By showing that this mechanism could produce binary asteroids, they were able to reproduce the observed fraction of doublet craters on the Earth, Venus, and Mars if most ECAs are rubble-piles.

Thus, tidal disruption of rubble-pile ECAs, if common, could provide a source for a substantial fraction of the small bodies which impact the Earth.

3. Numerical model

In order to characterize the mass loss produced by tidal disruption near the Earth, we use the numerical techniques
described by Richardson (1993, 1994, 1995) to model close Earth flybys of aggregates of spherical particles held together solely by their own self-gravity (i.e. a rubble-pile). A fourth-order polynomial predictor–evaluator–corrector integration engine was used to advance the particle positions and velocities forward in time. To increase precision, the calculation was performed in the progenitor’s center-of-mass reference frame. Note that additional details and results will be provided in Richardson et al. (1997).

Our model is similar to those used in the past by Asphaug and Benz (1996), Solem and Hills (1996), and others. In fact, if we were to use the same non-rotating spherical progenitor that they do, we would obtain nearly identical results. Our runs, however, introduce several new features which allow us to more realistically treat encounters between rubble-pile progenitors and the Earth.

First, we give our progenitor an elongated shape which closely mimics the shapes of real Earth-crossing asteroids (McFadden et al., 1989; Ostro, 1993; Ostro et al., 1995a,b). Our progenitor, composed of 247 spherical particles, was given dimensions of 2.8 \times 1.7 \times 1.5 \text{ km (1.8 \times 1.1 \times 1.0 normalized)}, somewhat similar to the shape of Earth-crossing asteroid 4769 Castalia (Hudson and Ostro, 1995a). Other groups have so far only investigated spherical progenitors, which are intrinsically more stable against tidal disruption than other rubble-pile configurations (i.e. spheres have a lower potential energy).

Use of an elongated progenitor, however, complicates our test runs, since we must keep track of the rotation phase (orientation of the progenitor’s long axis) at perigee. We define this rotational phase using the angle \theta; when \theta = 0^\circ, the long axis or its projection in the orbit plane points directly towards the Earth.

Second, we allow our progenitor to rotate, treating spin periods of \( P = 4, 6, 8, 10, \) and 12 h. Previous models have used progenitors without spin, since (a) objects have a nearly equal probability of encountering the Earth with a prograde or retrograde spin, making the zero spin case a reasonable representative case, and (b) it is simpler. This “average” progenitor (\( P = \infty \)), however, does not necessarily produce the median break-up outcome. Our results indicate that the median break-up outcome is instead dominated by objects with prograde spins, which happen to be very susceptible to tidal disruption. To account for rotation, we need to define the orientation of the progenitor’s spin axis at perigee. We do so using two angles: \( \alpha \), the angle between the rotation pole and the normal of the progenitor’s orbit plane, and \( \beta \), the projected angle between the pole and the vector connecting the progenitor with the center of the Earth at perigee measured in the orbital plane.

Third, we define the trajectory of the progenitor near Earth as a hyperbola using two parameters: the progenitor’s encounter velocity at “infinity” (\( v_\infty \)), defined as the velocity of a body before the gravitational acceleration of Earth becomes significant and its perigee distance (\( q \)). Previous models often simulated encounters between small bodies and a planet using a parabolic path. These trajectories can provide a useful approximation, but they are not as realistic as hyperbolic trajectories for most comets and asteroids near the Earth. The parameters \( q \) and \( v_\infty \), in conjunction with the rotation period of the progenitor (\( P \)), will play a critical role in determining whether a given encounter produces a tidal disruption.

Fourth, we include friction or energy dissipation between the particles using a coefficient of restitution (i.e. the ratio of the rebound speed to the impact speed) defined by the variable \( \epsilon \). For the cases shown in this paper, \( \epsilon = 0.8 \). Our tests show tidal disruption is largely insensitive to the choice of \( \epsilon \) as long as collisions are inelastic (\( \epsilon < 1 \)).

The bulk density of the progenitor was chosen to be 2 g cm\(^{-3}\) so it would correspond to typical km-sized body densities (e.g. Phobos and Deimos were found to have densities near 2 g cm\(^{-3}\) (Thomas et al., 1992); 243 Ida was estimated to have a bulk density near 2.0–3.1 g cm\(^{-3}\) (Belton et al., 1995)) and porous stone. Individual particles have densities of 3.6 g cm\(^{-3}\), similar to chondritic meteorites (Wasson, 1974). We do not report on our test runs with cometary bulk densities in this paper, because we do not expect many comets to tidally disrupt near the Earth. Long period comets typically have such high encounter velocities with Earth (mean encounter velocity is \( \sim 55 \text{ km s}^{-1} \) (Weissman, 1982)) that few are expected to undergo tidal disruption. The contribution of short-period comets to the near-Earth object population is thought to be negligible (Morrison, 1992). We do not address the issue of extinct comets within the Earth-crossing asteroid population.

The starting distance of the progenitor from the planet is 15 Roche radii, large enough to ensure planetary perturbations are negligible at the outset, but small enough to make exploration of parameter space practical. Each run is terminated at a post-encounter distance where most of the dynamical activity related to tidal disruption is completed (\( \sim 60 \text{ } R_\oplus \)).

4. Results

We recognize two types of tidal disruption when rubble-pile asteroids encounter the Earth.

4.1. Catastrophic or “SL9-type” disruptions (class “S”)

For very close or slow encounters, the equipotential surface of the rubble-pile asteroid is modified from a spheroid into a pencil-like shape by Earth’s tidal forces. Particles outside the new equipotential surface move or roll “downhill” to fill in that shape, though friction and their own inertia prevent them from arriving at their new positions instantaneously. As the pile recedes from the planet, the equipotential surface contracts, leaving many particles distributed along the former pencil-like shape. Gravitational instabilities cause most of these particles to clump into a number of roughly equal-sized bodies that look very much like a “string of pearls” (Fig. 1, top left). This disruption type is analogous to that seen when comet SL9 was pulled apart near Jupiter (Sridhar and Tremaine, 1992; Boss, 1994; Asphaug and Benz, 1994, 1996). We classify the disruption as “S” type when the largest remaining fragment retains less than 50% of the progenitor’s original mass. Numerical modeling supports the
idea that “S” class outcomes can produce crater chains on the Moon but not on the Earth (Bottke et al., 1997).

4.2. Rotational tidal disruptions (class “B”, “M”, “N”)

When a point mass encountering the Earth reaches peri-
gee, the gravitational acceleration pulling the object
towards Earth equals the centrifugal force trying to throw
it from the Earth. For real bodies such as our elongated
rubble-pile asteroid, however, this balance is lost. Instead
of experiencing equal forces, the end of the asteroid near-
est to Earth experiences a slight excess of gravitational
force pulling it radially towards Earth, while the end of
the asteroid furthest from Earth experiences a slight excess
of centrifugal force pulling it radially away from Earth.

This differential force results in a torque which pulls
the asteroid’s long axis towards the radial line stretching from
the asteroid’s center of mass to the Earth’s center. Objects
with longer moment arms at periapsis (i.e. spherical bodies
have uniformly small moment arms, elongated asteroids
have moment arms which vary depending on their orienta-
tion at periapsis) are more susceptible to tidal torque. In
many cases, tidal torque may accelerate the asteroid’s rotation rate and increase its length. (Variations on this
theme can be found in Boss et al. (1991), Boss (1994),
and Solem and Hills (1996).) If the torque is strong enough,
the ends of the distorted asteroid may be lost into space
along the asteroid’s equatorial plane. Keplerian shear
(wherein bodies closer to the asteroid’s center of mass
orbit faster than those further away) among these ejected
bodies produces spiral deformations similar to those seen
in models of stellar collisions (Benz and Hills, 1987; Benz
et al., 1989). We (arbitrarily) divide this disruption regime
into two groups: “B” breakup with mass shedding of
crumps and particles where between 10% and 50% of
the progenitor’s mass is lost (Fig. 1, top right); and “M” mild mass shedding of small fragments where less than 10%
of the progenitor’s mass is lost (Fig. 1, bottom left). A fourth
category, “N”, describes outcomes where no mass is lost
but tidal torques may still reshape the asteroid or change
its spin rate (Fig. 1, bottom right) (e.g. the strange shape
of 1620 Geographos reported by Ostro et al. (1995a, 1996)
may be an example of a tidally distorted body).

Figure 2 shows the results for progenitors with rotation
periods of $P = 6$ h encountering the Earth over varying
values of $q$ and $v_x$. “S” class events occur from $q \approx 2R_\oplus$
at $3 \text{ km s}^{-1}$ to $q \approx 1.01R_\oplus$ for velocities near $21 \text{ km s}^{-1}$.
Rotational tidal disruption (“B” and “M”) range from $q \approx 3R_\oplus$
at $3 \text{ km s}^{-1}$ to $q \approx 1.4R_\oplus$ at $21 \text{ km s}^{-1}$. In general,
we find that low values of $P$, $q$ and $v_x$ result in more
catastrophic disruptions. Our results, however, do not
always follow a simple pattern (e.g. the “N” outcome for
$q = 1.4R_\oplus$, $v_x = 21.1 \text{ km s}^{-1}$). This complication is due to
noise in $\theta$, the rotational phase of the progenitor at periapsis,
as $q$ and $v_x$ change. Computational limitations prevented
us from using the exact same value of $\theta$ for each choice of
$P$, $q$, $v_x$, but the overall trends in Fig. 2 are clear.

Though not shown, we have completed plots similar to
Fig. 2 for progenitors having a variety of different rotation
periods. We find that faster rotation periods ($P = 4$ h)
enhance disruption, increasing the range of $q$, $v_x$ values
where “S”, “B”, and “M” disruptions occur. Slower
rotation periods ($P = 8, 10, 12$ h), however, decrease this
range. We expect that tests using very long periods will
take us close to regimes explored using a spherical non-
rotating progenitor by Asphaug and Benz (1996) and
Solem and Hills (1996).

As explained previously, disruption can be assisted by
tidal torque, whose effectiveness changes depending on $\theta$,
the rotational phase of the asteroid’s leading long axis at
periapsis. For $-90^\circ \leq \theta \leq 0^\circ$ (i.e. when the leading long
axis is rotating towards the Earth in the prograde sense),
tidal torque and centrifugal force work together to
enhance disruption. For $0^\circ \leq \theta > 90^\circ$ (i.e. when the
leading long axis is rotating away from the Earth), tidal torque
and centrifugal force oppose one another to deter disruption.
Thus, to generate Fig. 2, we chose rotational phase
angles of $-90^\circ < \theta < 0^\circ$ for all computed runs.

The progenitor’s rotation pole orientation can also change
the outcome of an encounter. Figure 2 was completed
using prograde progenitors with $z = 0^\circ$. Real astero-
oids, however, have randomly oriented spin axes, with
an equal probability of encountering the Earth with a
prograde or retrograde rotation, making our results applic-
able only part of the time. Although computational
limitations prevented us from testing $\alpha$ and $\beta$ for each set of
$q$, $v_x$, $P$, and $\theta$, we did test enough cases to determine
the following trend: asteroids undergoing “S”, “B”, or
“M” class events when $z = 0^\circ$ continue to undergo the same
class of disruption so long as rotation is prograde (i.e.
$z < 90^\circ$), though the severity of mass shedding within a
class decreases as $z$ approaches $90^\circ$. Once rotation
becomes retrograde ($z > 90^\circ$), nearly all mass shedding
ends.

In summary, only half of the objects encountering the
Earth are likely to have their long axis oriented such that
a disruption event is likely. Of the rest, only half encounter
the Earth with prograde rotation (i.e. $z < 90^\circ$). Thus,
we find that an elongated Earth-crossing rubble-pile
asteroid has, at most, only a 25% chance of undergoing a
tidal disruption event each time it encounters the Earth.
These results can be used to predict how many Tunguska-
sized objects can be produced from ECAs by tidal forces.

5. Production of Tunguska-sized bodies by tidal disruption

The production frequency of TSBs from tidal disruption
can be estimated by combining the following components.

5.1. Map of tidal disruption outcomes near the Earth

Figure 2 shows the critical encounter parameters ($q$, $v_x$)
needed to produce a “S”, “B”, or “M” class disruption for
a $P = 6$ h prograde progenitor. Similar maps have been
produced for other rotation periods ($P = 4, 8, 10, 12$ h).
Since it is computationally prohibitive to map disrup-
tion outcomes for all possible values of $\theta$, $z$, and $\beta$
while varying $P$, $q$, and $v_x$, we test a more limited set
and treat the remainder statistically, dividing our estimate of

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Fig. 1. Snapshots of four classes of tidal disruption. In decreasing order of severity: (Top left) "S", a "Shoemaker-Levy-9-type" catastrophic disruption where the progenitor forms into a line of roughly equal size clumps (i.e. a "string of pearls") and leaves less than 50% of its mass in the largest fragment; (Top right) "B", a break-up with mass shedding of clumps and single particles, leaving the progenitor with 50–90% of its original mass; (Bottom left) "M", mild mass shedding of clumps or particles, leaving the progenitor with over 90% of its original mass; and (Bottom right) "N", no mass loss but possible reshaping of the progenitor accompanied by spin-up or spin-down
the disruption frequency by 4 based on the results presented in Section 4.

5.2. Probability distribution of ECA encounter velocities with the Earth

Assuming the 197 ECAs discovered as of April 1996 (from the Minor Planet Center via the database of D. Tholen) provide a representative sample of the entire ECA population, we used the technique of Bottke et al. (1994a,b) to calculate the probability distribution of encounter velocities with Earth (Fig. 3). The average encounter velocity \(<v_x>\) for this distribution is 12.47 km s\(^{-1}\), though many different values of \(v_x\) were used to generate our results.

5.3. Probability of ECAs encountering Earth

Using the same technique and ECA population described above, we calculated the average intrinsic encounter probability of ECAs with Earth: \(<P>_0 = 1.12 \times 10^{-18} \text{ km}^{-2} \text{ yr}^{-1}\). The encounter probability for a given asteroid was found by multiplying this value by \(q^2\) (\(\pi\) is already included in \(P_0\)) and by the gravitational focusing factor \((1 + v_0^2/v_e^2)\), where \(v_0\) is the escape velocity of the Earth at a distance \(q\) from its center.

5.4. Probability distribution of rotation periods among ECAs

The rotation period distribution of asteroids smaller than 10 km can be approximated as a Maxwellian with a mean period of 6 h (Fig. 4) (A. Harris, personal communication). Since Harris’ results (Harris, 1996) imply that no asteroid is currently in a state of tension, this distribution is truncated at 3.1 h (i.e. where our test asteroids would fly apart from centrifugal force). The distribution is also scaled for the 20% of the ECA population which are extremely slow rotators (e.g. 4179 Toutatis (Hudson and Ostro, 1995b)). For this calculation, we assume such bodies cannot tidally disrupt, though this approximation may be overly conservative (e.g. Asphaug and Benz, 1996).

5.5. Size–frequency distribution of (rubble-pile) asteroids in the ECA population

The ECA size–frequency distribution is shown in Fig. 5 (Morrison, 1992). This distribution was calculated using
data taken from the lunar cratering record, the terrestrial cratering record, and microbarograph records of atmospheric explosions (G. Shoemaker, personal communication). At the right-hand side of the size distribution, we insert the three largest known ECAs (9.6 km, 11 km, 12 km). Since the cratering history of the Moon suggests the impact rate in the Earth–Moon system has been constant over the last 3 Gyr (Grieve and Shoemaker, 1994), we assume the ECA population is in a steady-state. We also assume that rubble-pile asteroids must be 250 m in diameter or larger, the limit where catastrophic disruptions are controlled by the self-gravity of the target rather than its physical strength (Lowe and Ahrens, 1996). Approximately 40,000 ECAs have diameters larger than 250 m, with an uncertainty factor of two.

Integrating these components, we estimate that the total mass shed by rubble-pile ECAs is nearly $6 \times 10^{10}$ g yr$^{-1}$. This result is relatively insensitive to modifications to either end of the ECA size–frequency distribution: increasing the rubble-pile limit to 1 km only decreases the mass shedding rate by 15%, while decreasing the size of the largest ECA to 7 km decreases the rate by 25%.

We believe it is premature to predict the size–frequency distribution of material shed during a tidal disruption event, since we have only tested progenitors composed of spherical particles which are 250 m in size. Future work will examine this issue using a range of particles sizes and a greater number of small particles. Nevertheless, we can use our results to set some reasonable upper limits. If all the mass shed in tidal disruptions ($6 \times 10^{10}$ g yr$^{-1}$) were in the form of TSBs (50 m objects), their production rate would be 0.4 yr$^{-1}$, comparable with the injection rate of TSBs entering the 3:1 or $v_\pi$ resonances (one object per year (Menichella et al., 1996)). Since neither the size distribution of component material in a rubble-pile nor the supply rate of 50 m bodies from the resonances to the
near the Earth once every 210 000 yr, “S” and “B” events once every 120 000 yr, and “S”, “B”, “M” events once every 55 000 yr. The disruption of such an Earth-crossing asteroid should place multiple small bodies into orbits similar to that of the progenitor until planetary close encounters cause the objects to spread.

6. Evidence for tidal disruption among ECAs

Since bodies encountering Earth with low $v_\infty$ orbits are more likely to undergo tidal disruption, an examination of this region of phase space should show a greater abundance of tidal ejecta and tidally disrupted/distorted bodies. To map these low $v_\infty$ regions, we calculated mean $v_\infty$ values between test bodies spaced at regular intervals in $(a, e, i)$ space and the Earth using the technique of Bottke et al. (1994a, b) (i.e. the test bodies have semimajor axes $a$ between 0.05 and 4.0 AU, separated by $\Delta a = 0.05$ AU; eccentricity $e$ between 0.0 and 0.99, separated by $\Delta e = 0.01$, and inclination $i$ between 0° and 35°, separated by $\Delta i = 5°$).

Figure 6 shows two velocity contour maps produced from these results. Contours have units of km s$^{-1}$. Figure 6a shows that test bodies with 5° inclination have low $v_\infty$.}

Fig. 5. Estimated number of Earth-crossing asteroids larger than a given diameter (based on Morrison (1992)). The uncertainty in the distribution is a factor of 2

Fig. 6. Contour plots in $(a, e)$ space of mean $v_\infty$ values for test bodies encountering the Earth with (a) $i = 5°$, and (b) $i = 20°$. Contours have units of km s$^{-1}$. The lowest velocities are found where $e$ is small and perihelion ($q$) and aphelion ($Q$) are near 1 AU
values when $e$ is small and perigee ($q$) and apogee ($Q$) are near 1 AU. Figure 6b ($i = 20\degree$) shows a similar trend, though the higher inclination raises the lowest $v_\infty$ level enough to inhibit most tidal disruptions. Since ECAs generally adhere to the same $v_\infty$ contours as their progenitors (Bottke et al., 1996c), tidal ejecta should be common in the low $e$, $i$ regions of $\Sigma$CA space.

Low $v_\infty$ ECAs collide with the Earth more frequently than other ECAs. They also penetrate Earth’s atmosphere more deeply before exploding, such that objects smaller than 50 m may be capable of causing Tunguska event-like effects (Passey and Melosh, 1980). If a substantial fraction of small ECAs is tidal ejecta, Tunguska-type events may occur somewhat more frequently than predicted.

Tidal disruption in this region should enhance the population of Tunguska-sized ECAs and deplete the population of rubble-piles. A qualitative examination of the orbits and diameters of all known ECAs may corroborate our results. We caution, however, that the observed sample of ECAs (197) is so small that it is unlikely to be representative of either the km-sized ECAs (2100) or the 50 m ECAs ($\sim 10^5$) (Morrison, 1992): at best, the ECA population is only complete to absolute magnitude $H = 13.5$, corresponding to a 6 km “S” class asteroid or a 12 km “C” class asteroid (Rabinowitz, 1994). In addition, we know this sample is biased, since observers look for asteroids near the ecliptic and at opposition, where they can take advantage of increased brightness, increased numbers, and favorable rates of motion (Jedicke, 1996).

Figure 7 shows the orbital positions of these bodies in $(a, e)$ space and $(a, i)$ space. Any asteroid larger than 3 km is plotted with a large open circle, while any asteroid smaller than 200 m is plotted with a small open circle. The remaining asteroids are plotted with open circles linearly scaled between these limits. Asteroids crossing Earth’s orbit lie between the $q = 1$ AU and $Q = 1$ AU lines, while asteroids crossing the orbits of the other planets lie between other $(q, Q)$ lines. For example, asteroid 1620 Geographos ($a = 1.2455$ AU, $e = 0.3354$, $i = 13.3\degree$) crosses the orbit of Earth and Mars but not Mercury or Venus.

A qualitative examination of Fig. 7 reveals many small bodies at low $e$, $i$. Few large bodies with low $i$ can be found near $q = 1$ AU, though it is not clear if tidal forces or collisions with the Earth is wholly responsible. Nevertheless, these structural features are consistent with the implications of tidal disruption results and Fig. 6.

Interestingly, it has been suggested that an “excess” number of 10–50 m ECAs may exist in the low $e$ region

![Earth-crossing asteroid (ECA) population](image)

Fig. 7. Orbital positions and diameters of 197 Earth-crossing asteroids, plotted in $(a, e)$ and $(a, i)$ space. Any asteroid larger than 3 km is plotted with a large open circle. Any asteroid smaller than 200 m is plotted with a small open circle. The remaining asteroids are plotted with open circles linearly scaled between these limits. Asteroids crossing Earth’s orbit lie between the $q = 1$ AU and $Q = 1$ AU lines, while asteroids crossing the orbits of the other planets lie between other $(q, Q)$ lines. Few large asteroids are found at low $e$, though many small asteroids are located there. Small asteroids are also found at low $i$, though this may be the result of observational selection effects. Note that these trends match our expectations for an asteroid population modified by tidal forces (i.e. tidal disruption is likely when encounter velocities are low; compare this region with the low velocity region shown in Fig. 6)
relative to expectations based on the number of large ECAs seen elsewhere (Rabinowitz et al., 1993; Rabinowitz, 1994). If real, few plausible sources other than tidal forces exist to produce this localized population (Bottke et al., 1996c). The observational biases in the region, however, are difficult to calculate (for more detail, see Jedick (1996)). More observational data is needed to verify Rabinowitz’s claim.

7. Conclusions

We briefly summarize our results from this paper:

- Rubble-pile asteroids, after experiencing a close approach with Earth, frequently undergo tidal disruption, which can produce significant numbers of Tunguska-sized bodies.
- These disruptions are common where encounter velocities with Earth are low, corresponding to low values of $e$ and $i$. These disruptions may explain the excess population reported by Spacewatch (Rabinowitz et al., 1993; Rabinowitz, 1994).
- Our calculations show that an average mass production rate (upper limit) of 0.4 Tunguska-sized (50 m) objects per year is possible, and that this rate may be comparable to the ECA resupply rate of similarly sized bodies from the main belt.
- The size and orbital distributions of the known ECAs are consistent with the results of tidal disruption, which should be considered a positive argument that tidal forces play a prominent role in ECA evolution.

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References


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