Asteroids, Comets, Meteors 1991, pp. 101–108
Lunar and Planetary Institute, Houston, 1992

DEBRIS ABOUT ASTEROIDS: WHERE AND HOW MUCH?

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We summarize several recent findings on the size and shape of the region within which material can stably orbit an asteroid. If the asteroid (with assumed density 2.38 g/cm^3) *circles* the Sun at 2.55 AU, co-planar prograde material will remain trapped whenever started on unperturbed circular orbits at less than about 220 R_A (asteroid radii); co-planar retrograde particles are stable out twice as far. Our 3-D stability surface, which encloses several hundred numerically calculated orbits that start with various inclinations, is shaped like a sphere with its top and bottom sliced off; its dimensions scale like the Hill radius $=(\mu/3)^{1/3}R$, where μ is the asteroid-to-solar mass ratio and R is the asteroid's orbital radius. If the asteroid moves along an *elliptical* orbit, a fairly reliable indicator of the dimensions of the hazard zone is the size of its Hill sphere at the orbit's pericenter. Grains with radii less than a few mm will be lost through the action of radiation forces which can induce escape or cause collisions with the asteroid on time scales of a few years; interplanetary micrometeoroids produce collisional break-up of these particles in ~10^4 yrs. The effects of *Jupiter* and of asteroids that pass close to the target asteroid allow particles to diffuse from the system, again shrinking the hazard zone.

None of the considered sources--primordial formation, debris spalled off the asteroid during micrometeoroid impact, captured interplanetary particles, feeder satellites, etc.--seem capable of densely populating distant orbits from the asteroid. No certain detections of debris clouds or of binary asteroids have been made. Thus it seems highly unlikely that a spacecraft fly-by targeted at 100R_A from the asteroid over its orbital pole would encounter any material.

INTRODUCTION

Current NASA policy mandates that all outer solar system missions be devised so as to explore minor planets near any planned flight trajectory. In order to design observations properly, and more fundamentally in order to ensure a spacecraft's safety, mission planners need to know which regions of space surrounding the target asteroid might be dangerous and/or interesting. Thus critical questions are *Where might material orbit stably about minor planets?* and *What are the mechanisms whereby debris might be supplied and/or lost from this locale?* These two questions are very different: the first is a well-posed problem in celestial mechanics for which a simple response, including an estimate of its probable correctness, should be possible; in contrast and by necessity, the answer to the second query is much less clear since one always has the nagging worries that some supply mechanism may have been overlooked or that circumstances in the solar system today (upon which models are based) may not represent conditions at the time when the asteroid and any associated material originated.

The first spacecraft flyby of an asteroid occurred on October 29, 1991, when the Galileo spacecraft swung past the small S-class asteroid 951 Gaspra (nominal radius R_A=10km; orbital semimajor axis a=2.2AU, eccentricity e=0.17). The Cassini and CRAF missions are scheduled to visit other members of the diverse asteroid population about ten years from now. The latter mission's primary target, of course, is a comet for which mechanisms to supply its debris cloud are quite different than in the asteroid case; nevertheless, our ideas on the zone of stability remain equally valid for particles orbiting a cometary nucleus as for those circling an asteroid.

STABILITY SURFACE

The dynamics of an infinitesimal particle moving in the gravitational field of two masses which circle their mutual center of mass (the circular restricted three-body or CRTB problem) is one of the most celebrated problems in mechanics (Szebehely 1967). While the particle's complete dynamics are generally not available analytically, a constant of the motion--the Jacobi constant, which is the total energy measured in the reference frame that rotates with the orbital rate of the two primaries--can be determined. By expressing this constant algebraically, in terms of the coordinates, restrictions can be placed on a particle's movement such that certain regions of space may be inaccessible to the particle once its initial conditions have been specified. These regions are bounded by zero-velocity curves (ZVCs) or Hill curves that the particle may not cross. Thus, whenever a particle near an asteroid has initial conditions such that the ZVCs do not enclose the asteroid, that particle can, but *is not required to*, leak away onto its own heliocentric path.

ZVCs are valuable indicators of regions of space actually visited by a particle, however, only for orbits that are prograde (i.e., moving in the direction of the orbital motion of the asteroid about the Sun) and co-planar (i.e., in the asteroid's orbital plane) (Chauvineau and Mignard 1990a, Hamilton and Burns 1991 [henceforth HB1]). The largest closed ZVC surrounding an asteroid is shaped like a football centered on the asteroid with the long axis pointing along the Sun-asteroid line (Szebehely, 1967). In the Sun's direction, this critical ZVC extends from the asteroid to the Hill radius, $r_H=(\mu/3)^{1/3}R$, while in the orthogonal directions it reaches about 2/3 as far. For an asteroid of density 2.38 g/cm^3 located at 2.55 AU, $r_H \sim 450R_A$. Particles that start within the critical ZVC with no initial velocity in the rotating frame will remain bound to the asteroid. Of course, if the particle begins with some velocity, the starting point at which escape can occur will generally be closer to the asteroid. For example, prograde particles that are started beyond the asteroid along the Sun-asteroid axis at distances greater than about $220R_A$ on orbits which without the Sun's presence would be circular are seen numerically to be lost in fewer than 20 years (HB1); for the specified initial speed, this distance corresponds to a ZVC that is just barely open. Retrograde, co-planar particles, for which the ZVCs are poor indicators of escape, are found numerically to be stably bound even if they begin on circular orbits about twice this large (Zhang and Innanen 1988, HB1).

HB1 explore the nature of 3-D orbits near the stability boundary over relatively short times (about 20 years) for a range of initial conditions (particles start with various orbital sizes close to the escape distance and are given a circular speed that can be tilted at various inclinations *i* out of the asteroid's heliocentric orbital plane). Figure 1 depicts the upper half of the surface formed by the union of several hundred weakly bound orbits; that is, in all HB1's integrations no particles that remained in the asteroid's vicinity were found beyond the plotted surface along any particular latitude-longitude wedge. The stability surface is seen to be shaped like a sphere that has its top and bottom sliced off. This shape occurs since the dimension for orbits at low latitudes off the asteroid's orbital plane is set by primarily retrograde particles ($150° < i < 180°$), those that are far and away the most stable ones due to the Coriolis acceleration, which is inward-pointing for such paths. HB1 find that the Coriolis term is much less effective in retaining objects started with $90° < i < 150°$ and in fact drives away orbits at lower *i*.

Several complications have been added to this simple unperturbed CRTB problem in order to better represent reality. Chauvineau and Mignard (1990b) and Chauvineau et al. (1991) study the influence of perturbations due to Jupiter and to stray asteroids that pass close to the target asteroid. They find a gradual diffusion of the Jacobi constant over time and, for those particles whose "energy" is increased by such perturbations, this is equivalent to a slow opening of the ZVCs. Hence some material that started long ago at distances close to, but within, the stability boundary will be lost; other debris will be more firmly held in the asteroid's gravitational grasp.

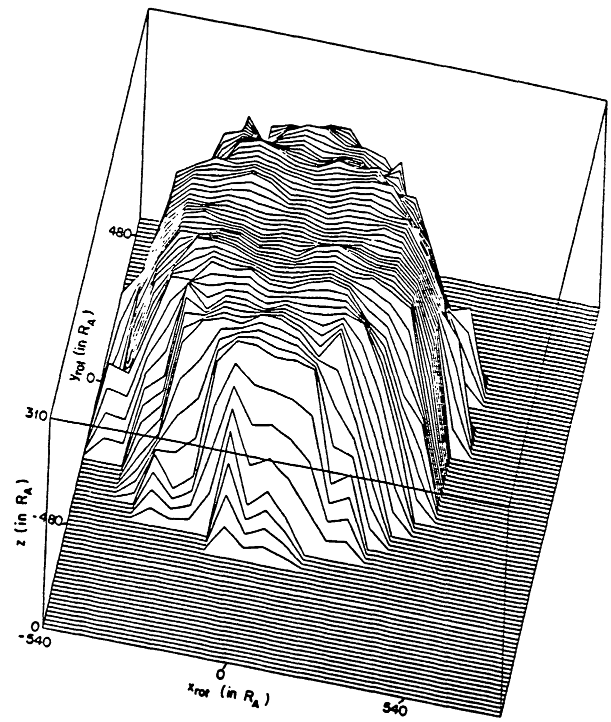

Figure 1:
Plot of the upper half of the stability surface. This corresponds to the maximum distance achieved by particles orbiting an asteroid of density 2.38 g/cm^3 moving on a circular orbit of radius 2.55 AU. The flattened top surface is at an approximate altitude of 285 R_A off the asteroid's orbital plane, and the surface drops precipitously to the roughly circular base region (r~480R_A). Clearly stable orbits are more closely confined in the polar regions, at least for these initial conditions. From HB1.

As soon as the asteroid's orbit has some eccentricity ($e \neq 0$), Jacobi constants and their associated ZVCs are no longer available to constrain motion. Nevertheless Hamilton and Burns (1992; henceforth HB2) have shown by analytic arguments and supporting numerical integrations that the opening of ZVCs *evaluated at the asteroid's pericenter* provide a good criterion for escape of co-planar prograde material, provided orbits are followed for only a few circuits of the asteroid around the Sun. For orbits that start at significant inclinations (60°<i<120°), the size of the hazard zone can be characterized remarkably well by decreasing distance results for an asteroid on a circular orbit by the factor 1-e, this amounts to scaling results as the Hill sphere calculated at the asteroid's pericenter. This same scaling appears to fail for purely retrograde orbits followed for 20 years; this at least partly reflects the fact that the integration times for retrograde particles were too short (HB2).

Solar radiation forces (Burns et al. 1979) are surprisingly effective in removing smallish particles from the circum-asteroidal environs. Accordingly, HB2 add radiation pressure to their numerical integrations; Fig. 2 shows the fate of several hundred initially circular prograde orbits around Gaspra after an elapsed time of 20 years. Moderate radiation pressure wreaks havoc on bound orbits, forcing particles to either strike the asteroid or flee the system. In fact, we find that bound orbits disappear altogether for particles less than 1 centimeter across! It's clear from Fig. 2 that bound, crash, and escape orbits are separated into three distinct regions; HB2 explain why different fates occur and derive theoretical curves that separate the regions. A similar plot results for retrograde orbits although, as expected, the Coriolis acceleration causes some enhanced stability when radiation pressure is weak. Orbits with substantial inclinations to the asteroid's orbital plane are somewhat more resistant to the mechanism causing particles to impact the asteroid and, accordingly, bound orbits are a bit more resilient. Nevertheless, all particles less than a few millimeters across either crash or escape; none remain bound. Although our results apply to specific initial conditions, we suggest that *any millimeter and smaller grains existing in Gaspra's environment will be transitory*. [In proof: Galileo's dust detector recorded no hits near Gaspra (Grün *et al.* 1991)] For scaling these results to other asteroids, we note that, if the dimensions of the minor planet are doubled while those of the orbiting particle are halved, identical equations of motion result.

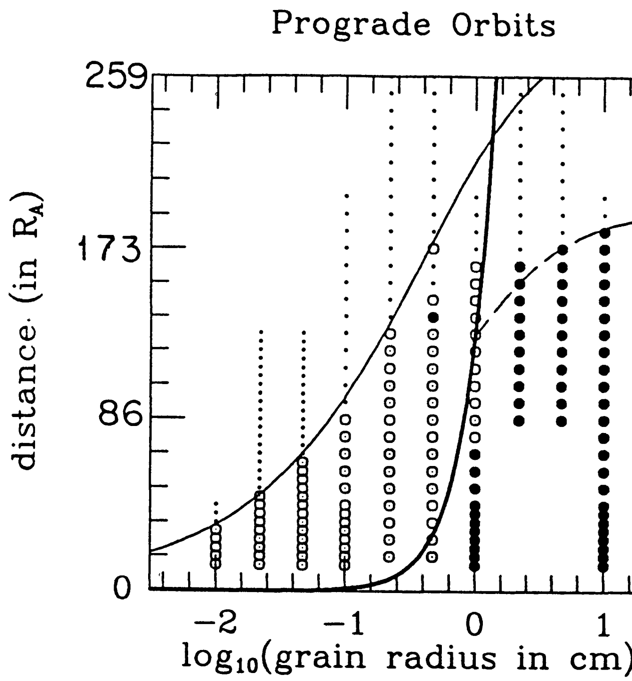

Figure 2:
The orbital fate of several hundred particles of different sizes started on prograde circular orbits around the asteroid 951 Gaspra, itself taken to have zero heliocentric eccentricity. A solid circle signifies an orbit that remained bound to the asteroid for at least twenty years, a small dot corresponds to an orbit that escapes to heliocentric space, and an open circle with a dot inside it is an orbit that crashes into the minor planet. Adapted for Gaspra (r_H~390R_A) from HB2 Fig. 15.

Over much longer times, the re-emission of absorbed solar radiation (Poynting-Robertson effect) causes orbits to lose energy and collapse. Time scales for the loss of heliocentric particles to the Sun or of planetocentric grains to their parent planet by this process are comparable (Burns et al. 1979). Thus particle lifetimes in the asteroid belt for totally absorbing grains are 10^8(r/cm) yrs; and grains smaller than 50 cm are eliminated over the age of the solar system. As described below, collisions actually determine lifetimes for grains larger than about a mm.

The crucial point to make is that *each* of the added complications to the simple CRTB problem tends to remove material from asteroid orbit. In this sense previous results are conservative.

SUPPLY AND LOSS

The above discussion says nothing about whether particles are likely to originate in those orbits that have been tested for stability nor about how long small circum-asteroidal debris could survive before its destruction by other means. Several supply mechanisms for circum-asteroidal satellites or debris come to mind: (i.) primordial processes; (ii.) recent collisional formation in a nearly catastrophic event; (iii.) captured interplanetary debris; (iv.) impact ejecta from the asteroid itself; and (v.) ejecta from a feeder satellite.

By analogy with the processes that are believed to form regular planetary satellites, asteroidal satellites or primordial debris (categories i and ii) should develop only near the asteroid, if at all. These bodies will not evolve outward rapidly, unless they are large satellites, in which case they become tidally locked with the primary's spin at synchronous orbit. However, it must be admitted that no one is certain how the small distant Jovian satellites originated: nevertheless those theories that are available do not admit remote satellites of an asteroid. Hence we do not believe that particles of categories i or ii will be found at distances more than a few tens of radii, if at all. Virtually no interplanetary particles that might collide in the outer reaches of the asteroid's Hill sphere (category iii) will be captured; such collisions are ineffective suppliers because they are infrequent and, more importantly, because they provide debris almost exclusively with velocities well above local escape speed.

Even though the above processes (i to iii) cannot generate material much near an asteroid, some debris should always be present at relatively great distances from any celestial object. In particular, the ambient micrometeoroid density will be enhanced by the gravitational attraction of the body; this effect is negligible for our case because typical relative velocities are large compared to escape speeds. A more significant source of debris may be the ejecta leaving the asteroid following micrometeoroid impacts (category iv). There are three types of ejecta: material that leaves at speeds less than escape speed (since this recollides quickly, it can be ignored); second, a small fraction of particles that are launched at near the escape speed and may have their orbits perturbed enough (e.g., by the Sun) to extend their lifetimes and thereby to increase their circum-asteroidal number density (this is potentially the most threatening class of ejecta); and finally the most common particles, from energetic impacts like those expected in the asteroid belt (see Fig. 17 in Burns et al. 1984); these leave with speeds greater than Gaspra's escape speed of order 10 m/sec.

Since hypervelocity impacts at the typical speed in the asteroid belt generate ejecta with a total mass 10^3 to 10^4 times that of the impactor, and since--ignoring the tiny asteroid's gravity--the departing ejecta's density drops off like the inverse distance squared, the density of departing ejecta will match that of the ambient micrometeoroids at about 30-100 R_A. Furthermore the path length through the debris cloud at a distance *d* from the asteroid is about *d*. Thus the hazard from the ejecta at any distance is at most a few times the hazard from the ambient micrometeoroids in the same vicinity. And, since the debris zone itself is so much smaller than the path across the full belt, the hazard from this cause can be ignored.

The most serious hazard could be posed by a different form of impact ejecta, collisional debris lost from another object--a so-called feeder satellite--which itself orbits the target asteroid at some distance. A larger fraction of debris from a feeder is trapped than from the primary because ejecta that barely escapes the feeder remains in orbit about the primary. Observations of the feeder would constitute a way to evaluate the danger of this source, but such are not feasible as no confirmed asteroid satellites have been discovered.

Particles in interplanetary space are destroyed by catastrophic fragmentation and by gradual erosion owing to micrometeoroid pitting and to sputtering by energetic particles. Although hunks of collisional detritus will be released in catastrophic impacts, the momentum transferred in the typical energetic event will generally be sufficient to permanently dislodge any circum-asteroidal particles since the latter are expected to be so weakly gravitationally tied to their primary. Davis *et al.* (1989; their Fig. 3) estimate that few, if any, objects smaller than 25 km can survive over the age of the solar system; they will be totally shattered and dispersed by the mutual hypervelocity collisions among members of the main asteroid belt. Surfaces in space are continually pelted by interplanetary micrometeoroids and by high-energy electrons and protons. Both of these processes cause a slow scouring of surfaces, which for our problem means that small grains have finite lifetimes; catastrophic fragmentation is even more effective. Grün *et al.* (1985; their Fig. 6) conclude that collisional lifetimes at 1 AU are shortest ($\sim 10^4$ yrs) for grains between 0.02 and 2 cm in radius; yet smaller particles have even shorter lifetimes due to Poynting-Robertson drag. While small grains are being destroyed, their orbits are inexorably collapsing due to the energy being drained by the Poynting-Robertson effect. Due to these ongoing destructive mechanisms, it is not enough to merely have once put material in distant orbit: if such objects are to be present today, they must either have been very large initially or there must be a continuing supply.

OBSERVATIONAL TESTS

Even though all observational evidence (direct searches, occultations, radar reflections, IRAS brightness levels across its several detectors, asteroid magnitudes in variable aperture photometers, etc.) to date can most simply be interpreted as indicating no debris, most planetary scientists feel that some fraction of the minor planets probably have companions; the remarkable radar discovery of the "contact-binary" nature of 1989 PB (Ostro *et al.* 1990), a tiny Apollo asteroid, supports this viewpoint as do doublet craters on the Earth (Melosh and Stansberry 1991). Motivated by earlier claimed discoveries of binary asteroids (summarized by Weidenschilling *et al.* 1989) as much as by concerns for the Galileo spacecraft's safety, Gradie *et al.* (1985) and Terrile and Smith (1985) used coronagraphs to scan the neighborhoods of a few asteroids; these searches found neither debris clouds nor asteroidal satellites. CCD searches have been undertaken by Gradie *et al.* (1987) and Stern and Barker (1992), also with negative results.

In the case of comets, radar returns indicate that at least Halley (Campbell et al. 1989) and IRAS-Araki-Alcock (Harmon et al. 1989) are enshrouded by extensive clouds of cm-or-bigger objects. Infrared data obtained by the IRAS spacecraft have provided convincing evidence for debris trails along the orbital paths of a half-dozen comets (Sykes 1986,1990); the material comprising these trails is thought to leave the comet at a relatively slow speed and hence to adopt orbits that are confined within a torus surrounding the comet's path. Similar physics should lead to analogous debris tori about the orbits of minor planets, albeit with much lower spatial densities because asteroids will be weak sources. The recently noted correlation between meteor streams and the orbits of some Apollo asteroids (Olsson-Steel 1988) endorses this viewpoint. Furthermore, some "asteroids"--notably 3200 Phaeton and perhaps Oljato--are likely defunct comets (Weissman et al. 1989). Thus one might wonder whether such trails might be hazardous to space missions that pass through the asteroid belt on their way to the outer solar system. The simple answer is that they pose very little risk as a straightforward consideration of optical depths indicates. The optical depth of the zodiacal cloud as a whole is $\sim 10^{-6}$, and the zodiacal bands are less than one-tenth that; the trails are even fainter, so that their optical depth is no more than $\sim 10^{-7}$-10^{-8}. Collisions are accordingly unlikely.

CONCLUSION

Beyond a fear of the unknown, there should be little to worry about as the Galileo spacecraft flies past 951 Gaspra at a planned distance of about 200 R_A in the asteroid's orbital plane. Had any similar consideration been made prior to the Pioneer and Voyager fly-throughs of the satellite systems of the giant planets, those regions would have almost surely appeared much more hostile than the environs of a small asteroid like Gaspra.

ACKNOWLEDGMENTS

This study originated and has been sustained through the interest of members of the Galileo Project, especially Clark Chapman, Torrence Johnson, Joseph Veverka and the late Clayne Yeates. The ideas on supply and loss mechanisms were developed at a 1984 JPL workshop chaired by JAB and attended by D. R. Davis, A. R. Dobrovolskis, A. W. Harris, K. R. Housen, K. Innanen, and P. Weissman among others. We thank D. R. Davis, A. W. Harris and S. J. Weidenschilling for commenting on an earlier version of this paper.

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