LARGE-SCALE EXPERIMENTAL PLANETARY SCIENCE MEETS PLANETARY DEFENSE: DEORBITING AN ASTEROIDAL SATELLITE.

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Introduction: Other than remote-sensing and spacecraft-derived data, the only information that exists regarding the physical and chemical properties of asteroids is that inferred through calculations,[1,2] numerical simulations,[3] extrapolation of experiments,[4] and meteorite studies.[5,6] Our understanding of the dynamics of accretion of planetesimals, collisional disruption of asteroids, and the macroscopic, shock-induced modification of the surfaces of such small objects is also, for the most part, founded on similar inferences. While considerable strides have been made in improving the state of asteroid science, too many unknowns remain to assert that we understand the parameters necessary for the more practical problem of deflecting an asteroid or asteroid pair on an Earth-intersecting trajectory. Many of these deficiencies could be reduced or eliminated by intentionally deorbiting an asteroidal satellite and monitoring the resulting collision between it and the primary asteroid, a capability that is well within the limitations of current technology.

The Rationale: Binary asteroids are being discovered with increasing regularity, and many of them are in orbits that are energetically favorable to visits by spacecraft. By applying a sufficiently strong retrograde impulse (Δv) or series of impulses to a suitably sized satellite, that body could be made to impact the primary asteroid. Such a collision would provide a wealth of information useful not only in deciphering the physical properties of both objects, but also in advancing our understanding of accretionary dynamics, low-velocity collisions on a large scale, ejecta dynamics in asteroid environments, rotational dynamics of small bodies, and a myriad of other phenomena. Deorbiting the satellite with explosive charges or impacts would provide additional information in areas such as that object's strength properties, seismic modification of small-body surfaces, changing the momentum of asteroids through impulsive events, the dynamics of regolith spallation, and mass exchange between asteroid pairs through impact, to name just a few. Small seismic stations emplaced on each body before initiation of the experiment would provide a unique source of data regarding the internal structures of the objects. While more elegant methods of applying the required Δv might exist,[7] the use of cratering events in this case would be more desirable, as they would serve both as sources of energy for the deorbit maneuver and as a means of probing many aspects of the body's characteristics and dynamical processes. Finally, understanding the vagaries of operating a spacecraft in a low-mass, multibody system would be very helpful should an asteroid-deflection mission ever be required: each identification of an asteroid as a bi-

Table 1. Select list of binary near-Earth asteroids and some parameters relevant to this study. The values in the first four columns were taken from the compilation provided by the Astronomical Institute of the Academy of Sciences of the Czech Republic (http://www.asu.cas.cz/~asteroid/binneas.htm), which also includes relevant references. Values for parameters not given at that site have been calculated from the listed data. All calculations assume that the two bodies are spherical.

Object	Primary diameter (km)	Satellite diameter (km)	Orbital semimajor axis (m)	Orbital period (s)	System mass (kg)	Satellite mass (kg)	Satellite-to-primary mass ratio	Material density (kg m^{-3})	Orbital velocity (cm s^{-1})	Required Δv (cm s^{-1})
2000 UG$_{11}$	0.23	0.14	410	6.62×10^4	9.6×10^9	1.8×10^9	2.3×10^{-1}	1.2×10^3	3.9	0.8
1999 DJ$_4$	0.4	0.20	800	6.38×10^4	7.4×10^{10}	8.3×10^9	1.3×10^{-1}	2.0×10^3	7.9	2.1
1998 RO$_1$	0.8	0.40	1360	5.23×10^4	5.4×10^{11}	6.1×10^{10}	1.3×10^{-1}	1.8×10^3	16	3.6
1998 ST$_{27}$	0.8	0.10	4000	3.60×10^5	2.9×10^{11}	5.7×10^8	2.0×10^{-3}	1.1×10^3	7.0	3.8
2002 BM$_{26}$	0.6	0.12	3000	2.59×10^5	2.4×10^{11}	1.9×10^9	8.0×10^{-3}	2.1×10^3	7.3	3.9
1996 GT	0.8	0.16	1200	4.28×10^4	5.6×10^{11}	4.4×10^9	8.0×10^{-3}	2.1×10^3	18	4.3
2000 DP$_{107}$	0.8	0.30	2640	1.52×10^5	4.7×10^{11}	2.4×10^{10}	5.3×10^{-2}	1.7×10^3	11	4.5
1994 AW$_1$	0.9	0.48	2070	8.06×10^4	8.1×10^{11}	1.1×10^{11}	1.5×10^{-1}	1.8×10^3	16	4.7
1998 PG	0.9	0.27	1530	5.04×10^4	8.3×10^{11}	2.2×10^{10}	2.7×10^{-2}	2.1×10^3	19	4.9
2001 SL$_9$	1.0	0.31	1800	5.90×10^4	9.9×10^{11}	2.9×10^{10}	3.0×10^{-2}	1.8×10^3	19	5.2
3671 Dionysus	0.9	0.25	2340	9.98×10^4	7.6×10^{11}	1.6×10^{10}	2.1×10^{-2}	2.0×10^3	15	5.5
1991 VH	1.2	0.48	3240	1.18×10^5	1.5×10^{12}	8.7×10^{10}	6.4×10^{-2}	1.5×10^3	17	6.2
2003 YT$_1$	1.0	0.18	2700	1.08×10^5	1.0×10^{12}	5.8×10^9	5.8×10^{-3}	1.9×10^3	16	6.3
1996 FG$_3$	1.4	0.43	2380	5.81×10^4	2.4×10^{12}	6.7×10^{10}	2.9×10^{-2}	1.6×10^3	26	6.6
1999 KW$_4$	1.2	0.36	2520	6.28×10^4	2.4×10^{12}	6.3×10^{10}	2.7×10^{-2}	2.6×10^3	25	7.9
2002 CE$_{26}$	3.0	0.21	5100	5.76×10^4	2.4×10^{13}	8.1×10^9	3.4×10^{-4}	1.7×10^3	56	17.
1999 HF$_1$	3.5	0.84	7000	5.05×10^4	8.0×10^{13}	1.1×10^{12}	1.4×10^{-2}	3.5×10^3	87	27.

nary increases the odds that such a task would involve a multiple-object system.

Potential Target Systems: An impressive number of near-Earth binary systems has already been discovered, and many of their kinematic parameters have been determined. Table 1 presents a selection of candidate binary NEAs and a variety of parameters useful in this study. (In keeping with the spirit of this descriptive contribution, "ballpark" precision should be sufficient to demonstrate the feasibility of the proposed mission.) The systems are ranked in ascending order relative to the Δv required to cause a grazing impact between the satellite and primary, assuming here that both are spheres.

Compared to those of samples in the terrestrial meteorite collections, the densities calculated for most of these objects are very low. Because the masses of most of the satellites are so small relative to those of the primaries, the effect of including them in the density calculations is minor. Thus, most of the primaries in these systems appear to be porous and almost certainly weak in comparison to coherent meteorites. Without a reason to do otherwise, it is assumed here that the densities of the satellites are comparable to those of their parent asteroids.

The Deorbiting Process: The Δv required to deorbit each satellite is very small in the context of more typical planetary problems. Nevertheless, the mass to be moved is enormous on a human scale, and the total change in momentum Δp is correspondingly large. Compounding the difficulties caused by the sheer scale of problem is the well-known tradeoff of imparting an impulse to the satellite large enough to move it while keeping the applied energy at a level that would not fragment the object. This impediment could be sidestepped by applying a series of less energetic impulses from smaller impacts or explosive charges. As an example, consider the 140-m diameter satellite in the system 2000 UG_{11}, which has an (idealized circular) orbital velocity around its primary of just under 4 cm s^{-1}. Deorbiting this object would require a Δv of about 0.8 cm s^{-1}, which translates to a Δp of about 1.5×10^{12} kg·m s^{-1}. Such a value could be realized by ejecting 1% of the satellite's mass in the direction of and parallel to the velocity vector $\mathbf{v}$ at a speed of 84 cm s^{-1} or greater. Continuing the example, if five separate deceleration events were used to deorbit the satellite, each would be required to accelerate the equivalent of 3.5×10^{6} kg along $\mathbf{v}$. Assuming a depth/diameter ratio for the transient cavity of 1/3 [8] and an ejected volume equal to half the volume of that cavity, this mass would be represented by the ejecta from a crater 44 m in diameter. Realistically, the event would have to be modestly larger to accommodate the dependence of ejection velocity with distance from the energy source; conversely, if the optimum depth of burial of a charge could be effected, the crater could well be smaller. Also, the curvature of the small body would probably enhance the mass of ejecta with smaller components along $\mathbf{v}$;[9,10] this in itself is a reason to argue for more and smaller deceleration events. In any case, explosions or impacts of this magnitude should be well within the limits of current, non-nuclear technology.

There are many additional advantages of multiple deceleration events. Each would remove mass from the satellite, for instance, making subsequent events that much more effective in decelerating the satellite. Each step would represent a separate experiment under different conditions (*e.g.*, reduced satellite mass), so more would be learned about the transfer of momentum through such means. This approach would cause the eccentricity of the satellite's orbit to grow with each step, permitting better determination of each event's effect. A correspondingly greater predictability in the timing of the collision between the two asteroids would result, allowing optimal positioning of the observing spacecraft. Each event would be a separate probe into the outer layers of the satellite; it could be argued that comparison of the morphologies and morphometries of the resulting craters would provide more insight into subsurface structure and target strength than would observation of a single, large crater. Should it be possible to emplace seismic instrumentation on the satellite before the start of the deceleration campaign, the increased number of events would greatly enhance the variety and quality of those data. Finally, if a means of adjusting the effective depth of energy release were available (using penetrators to plant explosive charges, for example), the efficiency of the deceleration process could be varied as conditions warranted. In short, the success or failure of the project would not depend on a single, large event.

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