PLANETARY SCIENCE

Asteroid Hazard Mitigation Using the Yarkovsky Effect

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The geologic record shows that several large objects have impacted Earth during the past several hundred million years (My) (*1*, *2*), and a number of methods have been proposed for mitigating such hazards (*3*). Here, I propose an approach to impact hazard mitigation that takes advantage of a nongravitational perturbation on asteroid orbits known as the Yarkovsky effect. This effect is caused by thermal radiation from a body with nonuniform surface temperatures. Thermal photons leaving the surface carry momentum, producing a slight reaction force on the body, roughly normal to the surface with a magnitude that depends on the temperature of the surface at that point. The hottest point on the body feels the strongest force. Because there is a delay between the time when a point on the surface receives its maximum insolation and the time it reaches its highest temperature, there is a Yarkovsky acceleration component along the orbit, changing the semimajor axis, a. The other orbital elements are affected as well, but the effect on a is the most important. The physical principles behind this effect are well understood, but its precise orbital perturbations are difficult to calculate because they may depend on an asteroid's shape, spin vector, composition, and details of its surface character. Nevertheless, a sophisticated enough thermal model should yield accurate Yarkovsky perturbations for specific asteroids.

Because the Yarkovsky effect arises from the surface temperatures on a body, it can be sensitive to surface characteristics such as albedo and surface thermal conductivity, K_s. Therefore, the body's Yarkovsky mobility might be changed by modifying only the upper few centimeters of the surface.

Using a finite-difference method (*4*), I estimated the rate of change of semimajor axis, da/dt, caused by the Yarkovsky effect as a function of K_s (ranging from 10^{-3} to 1 W m^{-1} K^{-4}) for model asteroids whose characteristics resemble those of the stony near-Earth asteroids 6489 Golevka (Fig. 1), 1566 Icarus, and 1620 Geographos, with diameters of about 300 m, 1 km, and 2.5 km, respectively. To account for surface porosity, I scaled the surface density (in kg m^{-3}) with K_s as

$$\rho_s = \left\{1500 + \frac{500}{3}\left[\log(K_s \text{ W m}^{-1}\text{ K}^{-4}) + 3\right]\right\} \quad (1)$$

while the density of the interior is varied so as to maintain a bulk density of 2000 kg m^{-3} (*5*). Assuming that the Yarkovsky effect causes a to change at a constant rate da/dt during the period Δt, a body experiences a displacement Δr relative to its predicted position on a purely gravitational orbit of about

$$\Delta r \approx -\frac{3}{2}\mu^{1/2}a^{-3/2}\frac{da}{dt}(\Delta t)^2 \quad (2)$$

where μ is the gravitational constant times the mass of the Sun. Displacements associated with changes in all of the other orbital elements either oscillate or accumulate only linearly with time, so only the effect on a is important. By changing K_s, one may change da/dt, producing an offset $\delta\Delta r$ relative to the predicted position:

$$\delta\Delta r \approx -\frac{3}{2}\mu^{1/2}a^{-3/2}\delta\left(\frac{da}{dt}\right)(\Delta t)^2 \quad (3)$$

Fig. 1. Rendering of 300-m diameter near-Earth asteroid 6489 Golevka based on the shape determined with radar (*7*, *8*). Although not civilization-threatening, objects of this size have the potential to destroy cities. Some such objects might be deflected by modifying their surface properties and hence the Yarkovsky effect that they experience. [Image courtesy S. Ostro, Jet Propulsion Laboratory/NASA]

For the 1566 Icarus model, the difference in da/dt between the bare-rock and porous regolith cases corresponds to an offset of about 1400 km in 100 years. Moreover, because of the quadratic time dependence in Eq. 2, that asteroid may be moved nearly 10 times as far in 300 years, virtually assuring a near miss instead of a collision. da/dt scales roughly with the inverse of diameter, so a Golevka-like body could be displaced several times further during those periods. A 10-km body with similar characteristics could be displaced more than 1000 km during 300 years. On the other hand, Geographos' mobility is not dependent on K_s, so other means would be required to divert such a body.

Another way to alter a body's Yarkovsky mobility is to change its albedo. For a hypothetical 100-m spherical body with the spin axis normal to the orbital plane, Yarkovsky da/dt can be decreased by a factor of nearly 50 by changing the albedo from 0.1 to 0.9. Such a drastic albedo change may not be attainable in practice, but in some cases (for example, Geographos, whose Yarkovsky da/dt may not be K_s dependent), modifying the albedo might nevertheless be the best approach to deflecting the asteroid.

To estimate a loose upper limit (*6*) on the effectiveness of the Yarkovsky approach, consider a 1-km spherical stony body with $a = 1$ AU. According to the finite-difference calculation (*4*), such a body could experience a Yarkovsky da/dt as fast as 10^{-3} AU My^{1}. Assuming that the Yarkovsky effect is somehow completely turned off (say, by giving it an infinite surface thermal conductivity or by painting it white), Eq. 2 gives an offset of about 15,000 km in 100 years.

In practice, the difficulty of moving an asteroid with the Yarkovsky effect depends on the body in question. To blanket the surface of a bare 1-km body to a depth of 1 cm, deep enough to modify the diurnal thermal wave, would require about 250,000 tons of dirt, the mass of roughly 90 fully loaded Saturn V's (*7*). A useful albedo change might be attained with perhaps 1/10 this mass of material. One might instead shatter the surface to a depth of a few cm by saturating the surface with conventional explosives, but such a small body is likely to lose much of that material. If the hazardous body already has a thin surface veneer (which seems unlikely), it may be removed with explosives, thereby exposing a bare surface with different thermal properties than the original. One ton of TNT could remove a 1-cm layer of loose material from the surface of a 1-km body if properly delivered. Obviously, any mitigation must take into account the details of the body in question.

The Yarkovsky approach is not applicable to all hazardous asteroids. Depending on the body, it may require a century or more to be effective, and the orbits of some Earth crossers are chaotic enough that they cannot be predicted beyond a few decades. However, the Yarkovsky approach is feasible with current technology and does not require the launch of a nuclear warhead.

References and Notes

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2. P. Farinella *et al.*, *Astron. Astrophys.* **377**, 1081 (2001).
3. H. J. Melosh *et al.*, in *Hazards Due to Comets and Asteroids* (Univ. of Arizona Press, Tucson, AZ, 1993), pp. 1111–1132.
4. J. N. Spitale, R. Greenberg, *Icarus* **149**, 222 (2001).
5. D. Vokrouhlický *et al.*, *Icarus* **148**, 118 (2000).
6. A larger offset might be obtained if the body were initially covered with a low-conductivity regolith, but such a configuration is unlikely on such a small body.
7. The Saturn V rocket launched astronauts on their journey to the Moon during the Apollo program.
8. R. S. Hudson *et al.*, *Icarus* **148**, 37 (2000).

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