There's a small chance that the near-Earth asteroid Apophis will inflict widespread devastation in 2036.

the Most *Dangerous* Asteroid Ever Found

By Daniel D. Durda

FRIDAY, APRIL 13, 2029. An hour after sunset, amateur astronomers across western Europe and northern Africa gaze skyward to watch a 3rd-magnitude "star" drift ever so slowly westward through Cancer. It's not an artificial satellite but a 320-meter (1,050-foot) pile of rock called Apophis. Its barely perceptible, nearly degree-per-minute motion against the stars belies its grazing flight through the realm of our geostationary satellites.

Although not a threat in 2029, a quarter-century earlier Apophis had raised the eyebrows of astronomers worldwide and the awareness of many nonscientists to the global ramifications of the near-Earth-asteroid impact hazard.

Today, in 2006, it's not the 2029 close pass itself that merits our concern but the potential for an Earth impact just 7 years later. That possibility has astronomers and policymakers alike grappling for an appropriate international response to a rare but very real global threat.

Illustration by Daniel D. Durda

A Christmas Story

During the Christmas 2004 holiday, a couple dozen of us who study the near-Earth-object impact hazard received an e-mail stating that the next day, the two world centers for asteroid impact predictions (at the Jet Propulsion Laboratory in California and the University of Pisa in Italy) were going to announce the first-ever forecast of a possible impact with a Torino Scale value of 2. Roy Tucker (Goodricke-Pigott Observatory), along with David Tholen and Fabrizio Bernardi (University of Hawaii), discovered the asteroid, provisionally designated 2004 MN_4, while testing new equipment at Kitt Peak in June 2004 (*S&T:* April 2005, page 20). But then it was lost. It was observed again on December 18th, and astronomers realized that it was the same object seen in June.

Those independent observations over many months enabled astronomers to calculate an orbit precise enough to reveal a roughly 1-in-200 chance of the asteroid hitting Earth on Friday the 13th (of all days!) of April 2029, with a devastating force of thousands of megatons. Many of us in the impact-hazard community never expected to face a threat of this magnitude.

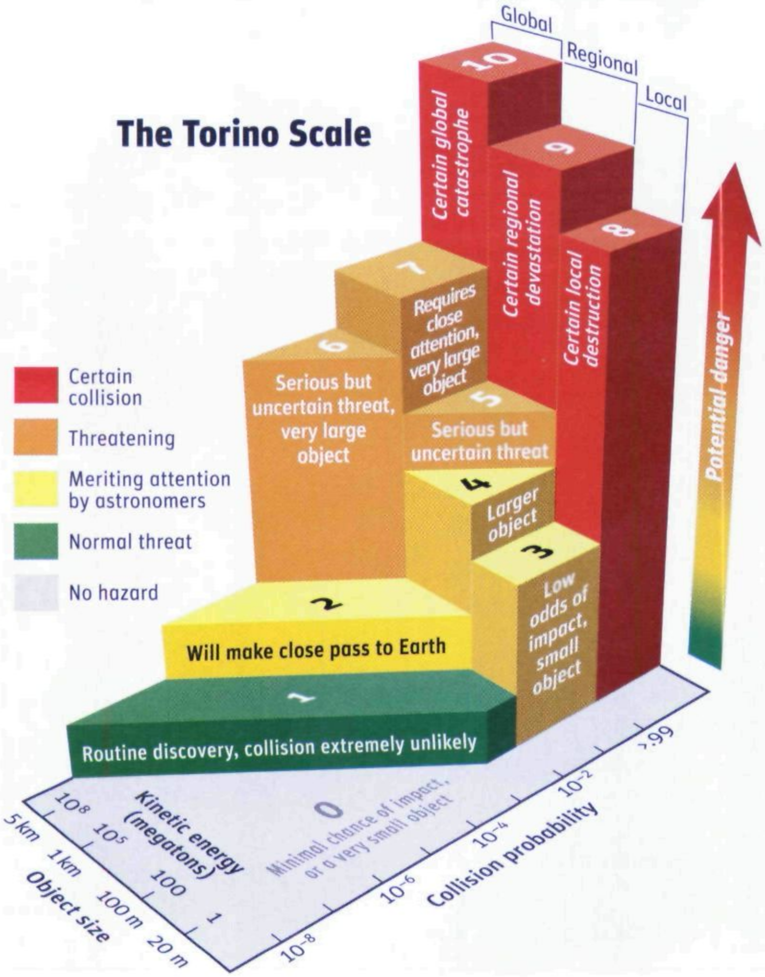
Determining the asteroid's size was an urgent issue, since one factor in a Torino Scale ranking is the severity of a potential impact. Initial uncertainties of 2004 MN_4's diameter allowed it to be anywhere between 200 meters and 1.5 kilometers. The impact of a 200-meter asteroid could devastate a major metropolitan area or spawn a terrible tsunami, but a 1.5-kilometer object could cause global catastrophe by destroying the ozone layer and perhaps throwing enough dust into the atmosphere to trigger worldwide climate effects.

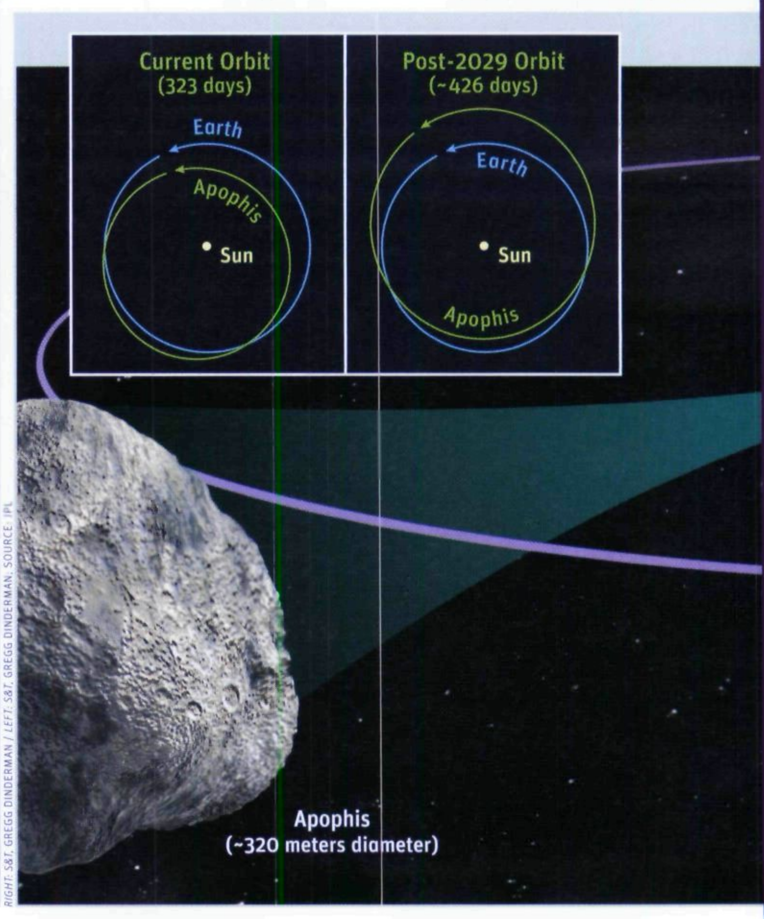
Over the next few days, professional and amateur astronomers around the world observed the asteroid and fed the positions to the Minor Planet Center. The JPL and Pisa groups used these new observations to update their orbit calculations and impact predictions. The calculated impact odds rose to 1 in 170 on December 23rd, 1 in 60 on December 24th, 1 in 40 on Christmas Day, and 1 in 37 on December 27th. The potential impact had reached 4 on the Torino Scale. Usually, when more observations of an asteroid are made, the odds of impact go down. But this was going in the opposite direction!

Although there was growing media interest in this evolving story, it didn't make the splashy headlines the way some previous, far-less-likely impact warnings had. Journalists go on vacation, too, during the holidays. And on December 26th a tsunami devastated Southeast Asia, and media attention was rightly focused on that tragic event.

A Close Shave

By December 27th it looked like the odds of a 2029 impact were going to climb to about 1 in 20. Fortunately, an extensive search turned up several images of 2004 MN_4 taken back on March 15th by the 0.9-meter Spacewatch telescope on Kitt Peak. Spacewatch's automated image-scanning software initially missed the asteroid because it was right at the system's magnitude limit. The odds of finding the object in old images were only about 10%. It is interesting to ponder





RIGHT: S&T: GREGG DINDERMAN / LEFT: S&T: GREGG DINDERMAN; SOURCE: JPL how we would have reacted had the odds of a substantial impact hung in there at 1 in 20 for several weeks or months.

With these newfound images, though, astronomers realized on December 28th that 2004 MN_4 would surely miss Earth on April 13, 2029. Further calculations showed that it would miss by a comfortable distance, about 5 Earth diameters.

In addition, ground-based near-infrared spectra acquired in early January 2005 by Andrew Rivkin (Applied Physics Laboratory) and Richard Binzel (MIT) suggested that the asteroid's composition was like that of a common, ordinary chondritic meteorite. This observation allowed us to estimate its albedo (reflectivity), which in turn yielded a diameter of about 320 meters.

In late January 2005, the Arecibo radio telescope (the world's largest, in Puerto Rico) was able to ping the asteroid, now named Apophis (the Greek name for the Egyptian god Apep, "the Destroyer"), with radar. With the radar data included in a new orbit determination, it turned out that some of the optically determined positions were in error. The asteroid is going to miss us by only half the distance calculated back on December 28th (*S&T:* May 2005, page 16). It will, in fact, pass within the orbits of our geosynchronous satellites and will sail across the European skies as a bright, 3rd-magnitude star, traversing some 40° in only 1 hour during its closest approach.

Something this big should pass this close to Earth only once every 1,500 years or so, yet Apophis will buzz us only a quarter century after its discovery. Are we missing something? Could our estimates of the impact rate be that far off?

Such concerns aside, Apophis provides a wonderful scientific opportunity. During its very close 2029 pass, gravi-

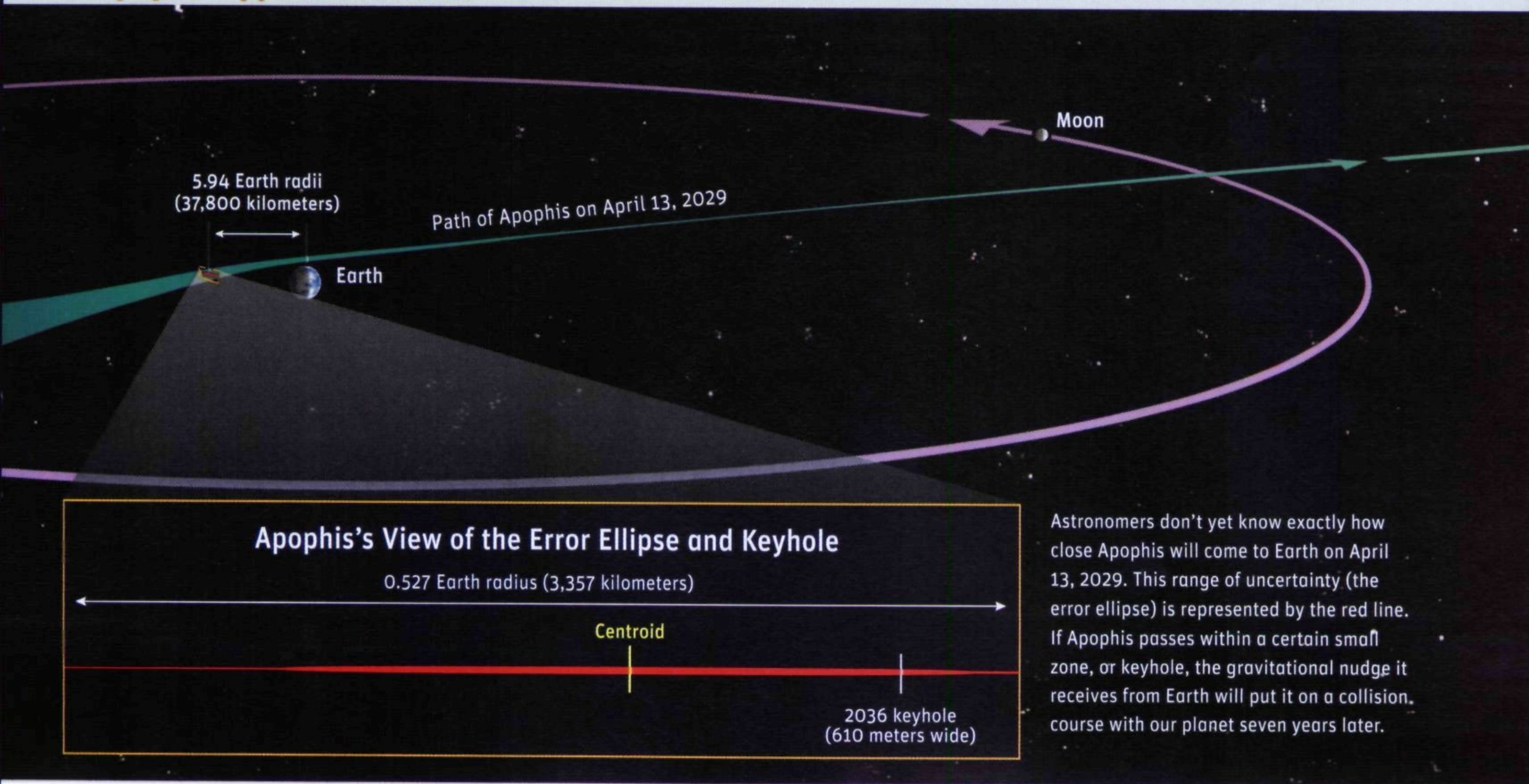
Apophis Found

It's hard to imagine how such a faint blip could cause so much fuss. But that's what happened when astronomers refined Apophis's orbit and realized it might collide with Earth later this century. The 90-inch (2.3-meter) Bok telescope on Kitt Peak in Arizona took this discovery image on June 18, 2004. It stacks three separate images together and shows stars as smeared star trails.

ROY TUCKER / DAVID THOLEN / FABRIZIO BERNARDI

Apophis Approaches Earth

Apophis will miss Earth on April 13, 2029. But the close call could put it on a course to hit Earth in 2036.



Astronomers don't yet know exactly how close Apophis will come to Earth on April 13, 2029. This range of uncertainty (the error ellipse) is represented by the red line. If Apophis passes within a certain small zone, or keyhole, the gravitational nudge it receives from Earth will put it on a collision course with our planet seven years later.

tational tides will likely alter its spin and may even subtly change its shape, although they won't be strong enough to tear the asteroid apart the way Jupiter ripped Comet Shoemaker-Levy 9 into a string of pearls.

Knowing years ahead that this asteroid will make a close approach gives us a chance to discern its internal structure. Is Apophis a solid shard of rock, or is it a rubble pile barely held together by its own feeble gravity? As Earth's tidal forces stretch and pull the asteroid, its interior will probably creak and pop with asteroidquakes. The echoes of these tremors will reveal boundaries between any significant internal structural components. Nature will be doing the energetically difficult part of an active seismic experiment for us — we need only implant a series of sensors and passively listen.

Not Out of the Woods Yet

As Apophis slingshots past Earth, gravitational forces will also bend its trajectory by about 28°. The size and period of its orbit will increase, and Apophis will spend more time outside Earth's orbit than it does now. But the details of the new trajectory depend on exactly where the asteroid makes its closest approach. And here lies the danger posed by this little mountain of rock.

There still remains one small region of space only 610 meters across that Apophis could pass through during its 2029 encounter that would bring it back to the same place exactly 7 years later. The problem is that Earth will be back at that same place too, and at the same time. So passage through this resonant-return "keyhole" allows for the possibility that Apophis could slam into our planet on April 13th of 2036.

At the moment, the error ellipse, or region of uncertainty, around Apophis's 2029 close approach has us keeping a close eye on the 610-meter-wide keyhole that would put it on a collision course for April 13, 2036. We need more observations to reduce the uncertainty, but unfortunately Apophis will be very difficult to see optically between about 2007 and 2011. This faint body spends most of its time inside Earth's orbit, closer to the Sun, where it remains hidden in twilight. In May 2006 Arecibo was just able to detect Apophis and nail its position. The orbital refinement shrank the error ellipse and displaced it somewhat away from the 2036 keyhole. With these and more recent optical observations, the chance that the asteroid might pass through that keyhole and impact Earth in 2036 is currently rated at about 1 in 48,000, down by a factor of 8 from earlier predictions.

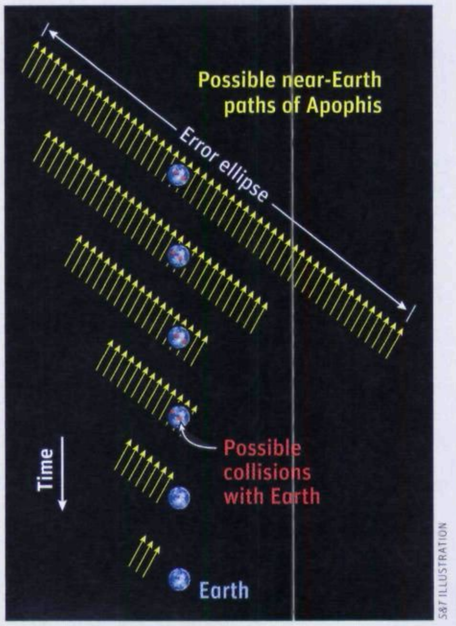
That's moving comfortably in the right direction, but it looks like we won't be able to say anything more definitive about Apophis's impact probability in 2036 until the early 2010s, when it next comes close to Earth and can again be observed by both optical telescopes and radar. By that time there is a 47,999-in-48,000 chance that the 2036 impact probability will drop to zero.

But if the 2036 keyhole remains within the even smaller error ellipse, we would probably send a spacecraft to place a radio transponder on the asteroid. In response to a request to NASA administrator Michael Griffin in 2005 to begin work on a transponder mission *now*, the agency conducted a very thorough analysis and determined that such a mission could be accomplished after the next good radar opportunity in 2013. The transponder's clear radio blips would allow us to track Apophis's motion more precisely than we could with passive radar observations alone. Those data will presumably show once and for all that the asteroid will not pass through the 2036 keyhole.

But then again, what should we do if by the early 2020s it still looks like Apophis has a significant chance of passing through the 2036 keyhole during its 2029 close pass? This possibility raises an important question: When does an object become threatening enough that action should be taken to deflect it? And since no national or international organization has been tasked with protecting Earth from impacts, who should make that decision, who should take action, who will pay for it, and who will be liable if something goes wrong with a deflection mission? A committee chaired by Apollo 9 astronaut Rusty Schweickart is working with the United Nations to address these issues.

Calculating Impact Probabilities

As observations in late December 2004 enabled astronomers to refine Apophis's April 13, 2029, trajectory, the error ellipse got smaller. But since Earth remained within that ellipse, that meant the chances of an impact actually increased, which was unusual. Fortunately, prediscovery observations made in March 2004 shrank the error ellipse so that Earth was safely outside of it, meaning the chance of an impact suddenly plunged to zero.



Gravity Tractor to the Rescue!

Researchers have proposed numerous techniques for deflecting a threatening asteroid onto a new trajectory. Large inflatable mirrors could focus sunlight onto the asteroid, or powerful lasers could zap its surface, vaporizing rocks. The comet-like jetting would slowly thrust the asteroid into a slightly different orbit, causing it to miss Earth.

Alternatively, scientists could slam something big into the asteroid, Deep Impact–style, to divert it or even break it up. A problem with this approach (and with nuclear weapons) is that you don't have much control over what happens to the asteroid after the impact, and you could end up with several large fragments. If some of them remain on an impact trajectory, you've made the problem even worse.

It's a good idea to have multiple tools at your disposal. A technique that might work well for one combination of lead time and object type might not work for another. One of our problems is that we don't really know the surface properties and internal structures of small asteroids. Observations of near-Earth asteroids, and laboratory studies of meteorites, suggest that their mechanical properties might range from solid nickel-iron to very porous, low-density rocky aggregates (September issue, page 34). How do you blast, grab ahold of, or work near the surface of a small body that has essentially zero gravity if you don't know whether its surface characteristics are akin to solid metal, powdery regolith, or something in between?

NASA astronauts Edward Lu and Stanley Love have devised an elegant solution to this problem: Park a spacecraft in close proximity to the asteroid, cant its highly efficient solar- or nuclear-powered ion thrusters to the side so their plumes don't hit the object, and hover beside it for several months or more with long, continuous thrusting. Due to the spacecraft's and asteroid's gravitational attraction on each other, the vehicle effectively tows the rock along with it using gravity as the towline.

If we launched a tugboat to Apophis before the 2029 close approach, we would only need to move the asteroid a few hundred meters to miss the 2036 keyhole, rather than several thousand kilometers to miss the entire planet. The tiny change in the asteroid's orbit could be accomplished with only a 1-ton solar-electric-propulsion spacecraft similar to NASA's low-cost Deep Space 1 mission.

This creative gravity-tractor concept solves the problem of not knowing the asteroid's surface properties, internal structure, or spin state. Since you don't have to land on the body or otherwise interact with its surface or interior, the gravity tractor provides a robust deflection technique that is also controllable. It can change the asteroid's orbital speed in any direction required to efficiently move the impact error ellipse off Earth. Scientists can continually monitor the progress throughout the deflection mission and take corrective action if necessary.

Large rocks do fall from the sky very rarely, but when they do, they can wreak widespread devastation and cause significant loss of life. Can we rationally evaluate the asteroid impact threat and undertake a national or international program to deal with it that is of sensible magnitude? Some feel that the appropriate response for dealing with this extremely rare threat is to do nothing. But you might think that since we have the knowledge and the technology at our disposal, we might as well not take the chance of going the way of the dinosaurs. ✷

Daniel D. Durda *is a senior research scientist at the Southwest Research Institute in Boulder, Colorado, where he studies the collisional evolution of asteroids and the effects of their impacts on Earth. He is also the president of the B612 Foundation (www.b612foundation.org), a group of scientists working to mitigate the impact threat.*

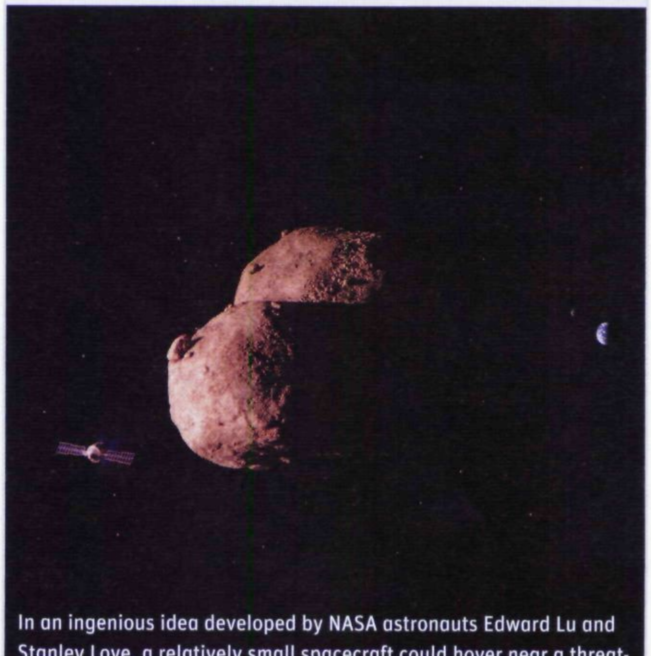
International Issues

In late December 2004, astronomers calculated Apophis's possible impact points were it to hit in 2029. If you plot this trajectory on Earth's population-density map *(below)*, you can hardly imagine a more dangerous path. Imagine what might have transpired if this had been announced and perhaps misreported by the media.

In the future, should scientists make this type of information public, given the likelihood that the impact probability will quickly drop to zero as more observations of the asteroid's position come in? Or would it be irresponsible to keep the information secret, since it wasn't clear in late December 2004 whether or not the hazard level would hang in at Torino Scale 4 for many months?

Consider a more general issue. As an impact date approaches, observations will narrow down the location of ground zero. Suppose that some nation or nations act to move the asteroid off the impact trajectory so it will miss Earth. If their deflection mission were to fail before completing its job, it might pull the point of impact from country A to country B. We need to figure out how to deal with these international policy issues before such an event actually transpires.

S&T ILLUSTRATION



In an ingenious idea developed by NASA astronauts Edward Lu and Stanley Love, a relatively small spacecraft could hover near a threatening asteroid and fire its ion thrusters continually in a direction that would tug the object out of its threatening trajectory.

DANIEL D. DURDA