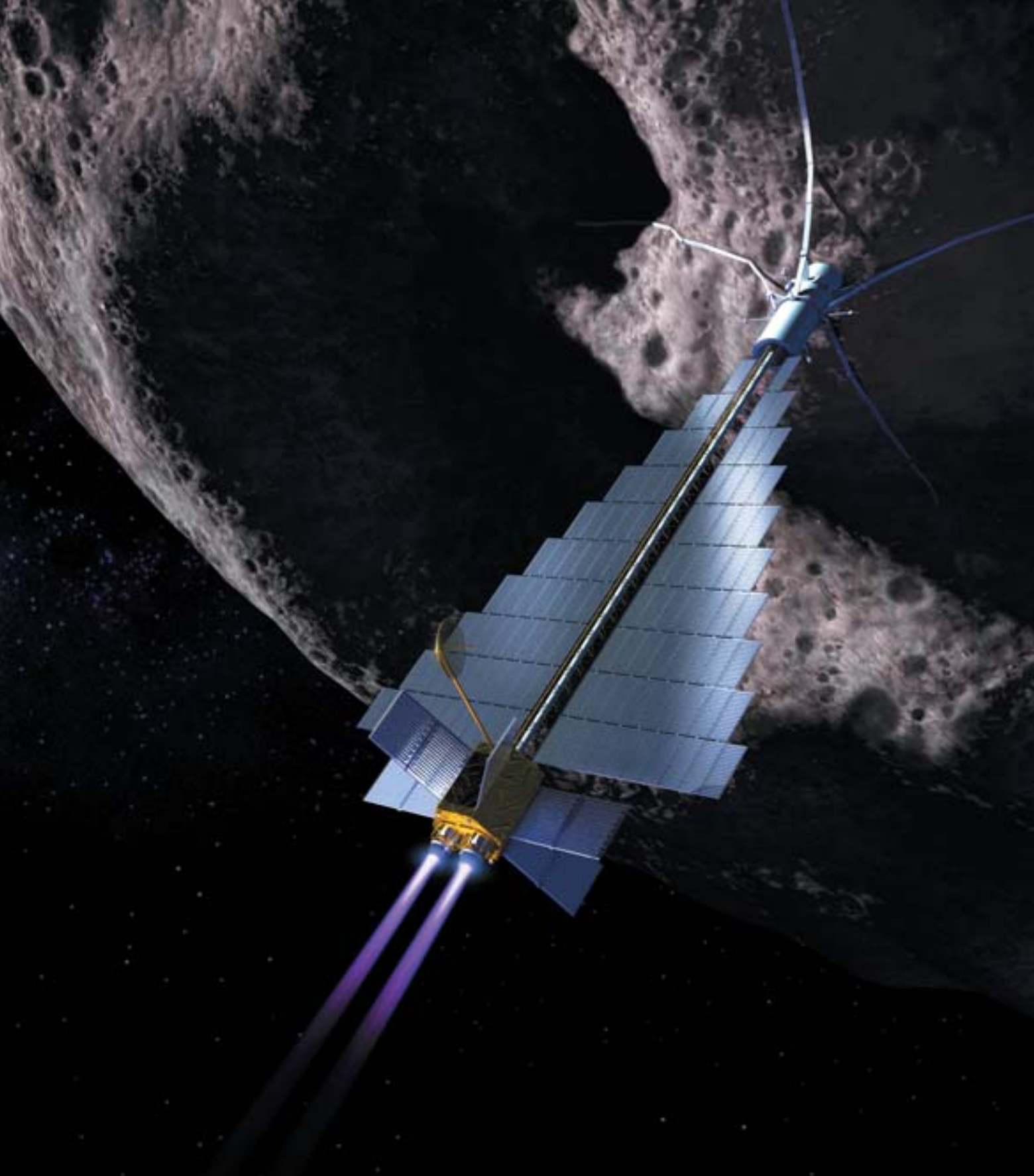


To prevent
an asteroid from
hitting Earth,
a space tug
equipped with
plasma engines
could give it a push

The Asteroid Tugboat

By Russell L. Schweickart, Edward T. Lu,
Piet Hut and Clark R. Chapman

On an average night, more than 100 million pieces of interplanetary debris enter Earth's atmosphere. Luckily, most of these bits of asteroids and comets are no bigger than small pebbles; the total weight of the 100 million objects is only a few tons. And our planet's atmosphere is thick enough to vaporize the vast majority of these intruders. So the debris usually streaks harmlessly overhead, leaving the bright trails popularly known as shooting stars.



SPACE TUG is shown pushing an asteroid in this artist's highly speculative rendering of a deflection mission. The tug could use plasma engines to steadily thrust the asteroid in the desired direction. An array of radiator panels would dissipate the heat from the craft's nuclear reactor, located in the section closest to the asteroid's surface. The segmented arms on the surface attach the tug to the asteroid and stabilize the craft.

When bigger objects slam into the atmosphere, however, they explode rather than vaporize. In January 2000, for example, a rock about two to three meters wide exploded over Canada's Yukon Territory with a force equivalent to four or five kilotons of TNT. This kind of event occurs once a year, on average. Less frequently, larger rocks produce even more powerful explosions. In June 1908 a huge fireball was seen descending over the Tunguska region of Siberia. It was followed by an enormous blast that flattened more than 2,000 square kilometers of forest. The consensus among scientists today is that a rocky asteroid

an explosion equivalent to 100 megatons or more of TNT. If a large asteroid crashes into the ocean, which happens in about 70 percent of impacts, it could create a tsunami that might kill millions of people by inundating coastal cities. Events of this kind happen once every 40,000 years or so. And an asteroid with a diameter bigger than one kilometer would strike Earth with the energy equivalent of 100,000 megatons of TNT, far greater than the combined energy of all the nuclear weapons in existence. Impacts of this size and larger have the potential to wipe out human civilization, and there is a chance of perhaps one in 5,000 that

unmanned space tug that would rendezvous with an incoming asteroid, attach to its surface and slowly push the body so that it misses Earth. (Because of the unique characteristics of comets, we do not address them in this proposal. New studies indicate that comets constitute only about 1 percent of the overall impact threat to Earth.) To push the asteroid, the space tug would use nuclear-powered engines that expel jets of plasma, a high-temperature mix of ions and electrons. We believe that a mission to

Rather than giving an asteroid a brief, powerful shove, the tug would deliver gentle pressure.



about 60 meters in diameter exploded some six kilometers above the ground with a force of about 10 megatons of TNT. The blast wave devastated an area approximately the size of metropolitan New York City.

Recent observations of near-Earth objects—asteroids and comets whose paths could intersect Earth's orbit—suggest that the chance of a similar event happening in this century is about 10 percent. Asteroids 100 meters across and larger pose an even more ominous threat because they will penetrate deeper into the atmosphere or hit the surface. Such an impact, which has a 2 percent chance of occurring before 2100, would cause

such a strike will occur in this century.

Can humanity prevent these catastrophes? Over the past decade scientists and engineers have proposed a variety of schemes to deflect an asteroid that is heading toward Earth [see box on page 58]. Several researchers have advocated detonating a nuclear weapon on or near the asteroid to either break it up or change its course, but the effects of a nuclear blast are difficult to predict, and that uncertainty has led many experts to view this option as a last resort at best. Recently interest has focused on more controlled options for shifting an asteroid's trajectory. For the past two years we have been studying the concept of an

demonstrate the asteroid-tug concept could be accomplished by 2015.

Why develop such a spacecraft now, before astronomers have identified any asteroids on a collision course with Earth? Because the system should be tested before it is urgently needed. By attempting to deflect an asteroid that is not on, or even close to, a collision trajectory, researchers will acquire the experience necessary to build a reliable defense. Potentially hazardous asteroids have not yet been studied in any detail; because we do not know much about their interior makeup, surface characteristics or structural integrity, we cannot know what will happen when a space tug nudges one. The best way to learn about these crucial aspects is to land a spacecraft on an asteroid and then try to move it. As a bonus, the mission would add to our understanding of asteroids, pioneer the way to asteroid mining, and demonstrate critical technologies for future exploration of the solar system.

What is more, NASA is already working on the key technologies needed for the asteroid tug. As part of the Prometheus Project, the space agency is trying to design nuclear reactors that could power ion-propulsion systems for interplanetary

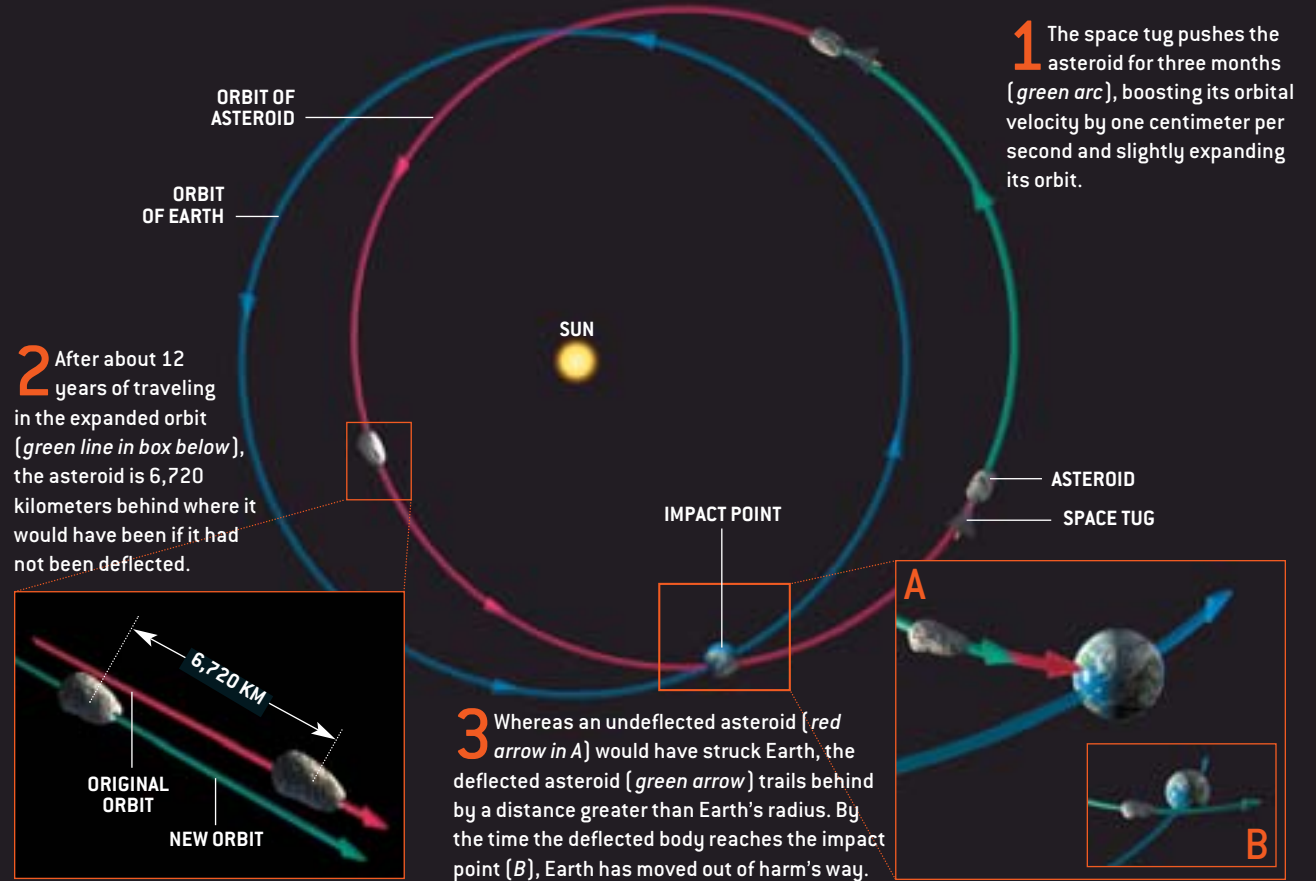
Overview/*Nudging an Asteroid*

- Near-Earth asteroids pose a threat to humanity. A direct hit by a 100-meter-wide asteroid would destroy a large city, and a one-kilometer-wide object could wipe out our civilization.
- Previous proposals for deflecting Earth-bound asteroids, such as nuclear explosions or kinetic-impact schemes, are unreliable. But a space tug equipped with plasma engines could provide a gentle push that would cause the asteroid to miss its rendezvous with Earth (assuming sufficient warning time).
- A mission to demonstrate the asteroid-tug concept could be accomplished by 2015. NASA is already developing nuclear reactors and propulsion systems that could be used by the space tug.

AVERTING A COLLISION

A SPACE TUG can alter an asteroid's orbit by pushing in the direction of its orbital motion. This diagram assumes that the

tug begins pushing 12 years before the projected impact and that the asteroid has an orbital period of 1.15 years.



spacecraft. NASA plans to integrate these systems into the Jupiter Icy Moons Orbiter (JIMO), a spacecraft that is expected to visit the Jovian moons of Ganymede, Callisto and Europa in the next decade. The same technologies could be applied to the greatest public safety project in history: warding off the doomsday rock that will sooner or later threaten humanity.

The B612 Mission

THE PROBLEM OF DEFLECTING an asteroid resolves into a timing issue. First, astronomers must detect the asteroid at least a decade before impact to provide time for the actions to take effect. Fortunately, with continued improvement in ongoing asteroid-detection programs, this is a reasonable expectation. To prevent the rock from hitting Earth, the most efficient plan is to either speed up the body by pushing it in the direction of

its orbital motion or slow it down by pushing in the opposite direction. Changing the asteroid's velocity alters its orbital period—the time it takes to go around the sun. Because Earth moves along its orbit at an average speed of 29.8 kilometers per second and its diameter is 12,800 kilometers, our planet takes 215 seconds to move half its diameter. If an asteroid were headed for a bull's-eye collision with Earth, the challenge would be to change the asteroid's orbital period so that it arrives at the rendezvous site at least 215 seconds before or after Earth does, allowing the body to whiz safely by our planet [see illustration above].

Applying a soft but prolonged push on the asteroid about 10 years before it is expected to hit Earth, the tug would need to boost the asteroid's velocity by only about one centimeter per second. This change would slightly expand the aster-

oid's orbit and lengthen the time it takes to travel around the sun. For example, for an asteroid with an orbital period of two years, a one-centimeter-per-second velocity change would increase its period by 45 seconds and create a delay of 225 seconds over 10 years—enough for the asteroid to miss Earth by a small margin. Alternatively, the space tug could slow down the asteroid, shrinking its orbit and reducing the period by 45 seconds; after 10 years, the asteroid would arrive at the rendezvous site 225 seconds before Earth does. Of course, if the space tug reaches the asteroid when it is closer to striking Earth, it would need to give the body a bigger push. This fact underscores the importance of early and accurate detection of all near-Earth asteroids [see box on page 60].

To demonstrate this concept and the technologies involved, we have proposed

the development of a space tug that could deflect a 200-meter-wide asteroid, which would cause regional devastation if it hit Earth. We have dubbed this test project the B612 mission (B612 is the name of the asteroid in *The Little Prince*, the well-known children's book by Antoine de St. Exupéry). A rocky 200-meter asteroid has a mass of about 10 billion kilograms. Rather than giving the asteroid a brief, powerful shove—which might shatter the body instead of altering its course—the B612 tug would deliver gentle pressure. The force would be only about 2.5 newtons, approximately equivalent to the

force required to hold up a glass of milk. But if this light nudge were applied for just over three months, it would be enough to change the asteroid's velocity by 0.2 centimeter per second. Should we be faced with an actual threat by a 200-meter asteroid, our small demonstration mission would either have to be scaled up by a factor of five or more to prevent the body from smashing into Earth, or else we would have to act at least 50 years before impact.

Because the force must be provided continuously for an extended period, the space tug's engines would require a sig-

nificant amount of fuel. An additional large supply of propellant would be needed to get the tug to rendezvous with the asteroid. The average velocity change to get from our planet to a typical near-Earth asteroid is about 15 kilometers per second—one third more than the velocity change required to escape Earth's gravity. The standard chemical rocket engines, which mix fuel with oxidizer in a combustion chamber, would be hard-pressed to propel a substantial spacecraft (and all the fuel needed to push the asteroid) to these speeds. Such a vehicle would require so much propellant to per-

Asteroid Roundup

THE VARIOUS PLANS for deflecting an Earth-bound asteroid fall into two categories: those that rely on brief but intense applications of force and those that involve gently pushing or pulling the body over a long time. The most frequently mentioned concepts are described below.

NUCLEAR EXPLOSIONS have been proposed in two schemes. The obvious one is to destroy the asteroid by blasting it to smithereens. The less obvious approach would be to detonate a nuclear device off to one side of the asteroid, which would intensely heat the surface facing the explosion. The vaporization of surface rocks on that side of the asteroid would accelerate it slightly in the opposite direction. The advantage of these options is that the technology

already exists and could be rapidly deployed. Theoretically, a powerful nuclear explosion could deflect a large asteroid that is just months from hitting Earth, a capability beyond that of any other technique. The problem, however, is that the results are neither predictable nor controllable. The explosion could split the asteroid into several large pieces, which might compound the problem rather than solve it.



NUCLEAR EXPLOSION might split an asteroid instead of changing its course.

Simply launch the largest spacecraft available and smash it into the threatening asteroid at as high a velocity as can be mustered. Given the extremely high relative velocities necessary to deflect a substantial asteroid, a major challenge would be guiding the spacecraft so that all its impact energy goes into moving the asteroid off course and not spinning the body or knocking off a small chip. And as with nuclear explosions, splitting the asteroid is also a concern.

A MASS DRIVER is a device built on the surface of the asteroid that would repetitively hurl rocks into space, causing the asteroid to accelerate slowly in the opposite direction. Throwing enough rocks

in the right direction would change the velocity of the asteroid enough to avoid a collision with our planet. The advantage of the mass driver is that it ejects materials from the asteroid itself, obviating the need to carry propellant from Earth. Throwing rocks, however, still requires a substantial energy source. The design of such a machine and its robotic installation on the asteroid's surface would be daunting tasks.

ABLATION is similar in concept to the standoff nuclear explosion but much slower. A small area on one side of the asteroid would be heated by a powerful laser flying near the asteroid or by sunlight reflected from a very large space mirror. Vaporized surface material would propel the asteroid in the desired direction. The attractive aspect of this option is that the asteroid's rotation is of no concern. But the laser or mirror must be able to maintain its position accurately to the side of the asteroid for a long period and therefore would require a substantial fuel supply. The optical elements of such concepts would also be vulnerable to coating by the ablating material from the asteroid.

SOLAR PRESSURE is another possible mechanism. A spacecraft would coat the asteroid's surface with highly reflective paint, which would change the radiation pressure caused by solar heating and very gradually alter the asteroid's course. But it is difficult to see this technique as a workable option given the massive amount of paint required and the difficulty of applying it to the surface.

LAND AND PUSH, the concept behind the asteroid tug, is very straightforward. The propulsion system required to get to the asteroid, which would also have to be developed for the other alternatives, is used to deflect the rock as well. The greatest advantage of this option is that it is fully controllable. The challenge lies in maneuvering the spacecraft and attaching it to the asteroid.

form the B612 mission that it could not be launched by a single rocket; dozens of heavy-lift rockets would be needed to boost all the components into low Earth orbit. Then the spacecraft would have to be assembled in orbit, which would drastically raise the mission's cost and delay the journey to the asteroid.

Our goal is to design a space tug that could be launched on a single heavy-lift rocket, such as a Proton, Ariane 5 or Titan 4. Because the tug must have a total mass less than about 20 tons, it needs extremely fuel-efficient engines. The primary measure of rocket efficiency is specific impulse, which is the thrust generated for each unit of fuel consumed per second. The most efficient chemical rockets have a specific impulse of up to 425 seconds when operating in the vacuum of space. (The units of specific impulse are seconds.) But the engines of our asteroid tug must have a specific impulse of 10,000 seconds.

This performance is not feasible for standard chemical rockets but is comfortably within the range of electric engines, which use electrical or magnetic fields to accelerate ions out the exhaust nozzle of the rocket. In this way, the engines can achieve much higher exhaust velocities than chemical rockets, which simply burn fuel and allow the expanding hot gases to escape out the nozzle. Ion engines with a specific impulse of 3,000 seconds have successfully flown in space. A promising new engine known as the VASIMR (Variable Specific Impulse Magnetoplasma Rocket) uses radio waves to ionize a gas and accelerate the plasma to even higher exhaust velocities [see "The VASIMR Rocket," by Franklin R. Chang Díaz; *SCIENTIFIC AMERICAN*, November 2000]. Rather than using a conventional nozzle, the VASIMR employs magnetic fields to direct the expanding stream of ions out of the rocket at specific impulses between 3,000 and 30,000 seconds.

Of course, there is a price to be paid for such high performance. Although plasma and ion engines are more efficient than chemical rockets, their thrust is much lower (because the high-temperature exhaust is so tenuous). Several ion

THE B612 MISSION

THE GOAL of the B612 mission is to significantly alter an asteroid's orbit in a controlled manner by 2015. The space tug would need to rendezvous with a target asteroid, attach itself to the surface and show its ability to maneuver the object.

1 The first objective of the space tug is to push the asteroid parallel to its spin axis, increasing its velocity in that direction by 0.2 centimeter per second.

2 The second objective is to torque the asteroid's spin axis by five to 10 degrees. For this step, the tug's engines must be parallel to the surface.

engines now under development could achieve specific impulses approaching the target of 10,000 seconds, but with the exception of the VASIMR, most electric engines generate less than 0.1 newton of force. Thus, many such engines would have to be ganged together to reach the desired thrust level of 2.5 newtons. Even when combined, the engines must push on the asteroid for a very long time to alter its orbit. Long-term operation has already been demonstrated, however: the ion engine on the Deep Space 1 spacecraft, launched in October 1998, accumulated 677 days of operating time.

To provide the required thrust, the

plasma engines would need about 250 kilowatts of electrical power (assuming an engine efficiency of 50 percent). This amount of power is considerably beyond the capability of the solar arrays typically used for small spacecraft. Even the enormous solar arrays of the International Space Station, when completed, will produce less than half this amount (and they will weigh more than 65 tons). Clearly, such an array is infeasible for a spacecraft that must weigh less than 20 tons in total. The only current technology that can steadily supply this much power for several years in a package that weighs just a few tons is nuclear fission.

THE AUTHORS

In October 2002 *RUSSELL L. SCHWEICKART*, *EDWARD T. LU*, *PIET HUT* and *CLARK R. CHAPMAN* formed the B612 Foundation, a nonprofit group dedicated to developing and demonstrating the capability to deflect asteroids from Earth. Schweickart, chair of the foundation's board, is a former NASA astronaut who piloted Apollo 9's lunar module in 1969 and served as the backup commander for the first Skylab mission in 1973. Lu, the foundation's president, is a current astronaut who e-mailed his contributions to this article while onboard the International Space Station. Hut is a professor at the Institute for Advanced Study in Princeton, N.J., whose main research interests are computational astrophysics and the study of dense stellar systems. Chapman, a scientist at the Southwest Research Institute in Boulder, Colo., is a member of the science team for the upcoming MESSENGER mission to Mercury.

The asteroid tug needs a simple, small and safe nuclear reactor. Fortunately, NASA has already proposed some new designs for spacecraft reactors, and one has undergone preliminary testing. An important safety feature in these new designs is that the nuclear fuel is minimally radioactive until the reactor has pro-

duced power for a significant amount of time. Because the reactor would be launched cold—that is, inactive—even a catastrophic launch accident would pose little environmental danger. If the entire uranium core of the SAFE-1000, an advanced space reactor being developed at Los Alamos National Laboratory, were

dispersed in a launch explosion, the radiation released into the environment would be only six to 10 curies—less than the total radiation contained in the walls of New York City's Grand Central Station. Ground controllers would send the command to activate the reactor only after it was safely in space.

Scouring the Sky

ON MARCH 18, 2002, newspapers and TV news shows around the world reported that Earth had just survived a near miss with a newly discovered asteroid named 2002 EM7. Astronomers observed the 70-meter-long rock four days after it passed within 461,000 kilometers of our planet, about 1.2 times the distance between Earth and the moon. Although it received quite a bit of attention, 2002 EM7 is just one of hundreds of thousands of asteroids that have come close to or crossed Earth's orbit. The international effort to detect and track these potentially threatening objects is called the Spaceguard Survey.

In 1998 NASA, at the urging of Congress, adopted the goal of detecting 90 percent of the 1,100 or so near-Earth objects (NEOs) larger than one kilometer in diameter. Halfway into the 10-year program, astronomers have found more than 660 NEOs of this size and more than 1,800 smaller bodies. Many of the asteroids currently being tracked were first seen as they were leaving Earth's vicinity, just as 2002 EM7 was. Fortunately, any asteroid destined to smash into Earth will most likely pass within a few lunar distances of our planet thousands of times before finally striking it. If researchers identify an object headed toward us, destined for an Earth impact, they will probably spot it decades or even centuries before it actually hits. The short-warning scenario, as dramatized in the 1998 movies *Armageddon* and *Deep Impact*, is exceedingly improbable.

Every time Spaceguard detects a new NEO, scientists make projections based on its orbit to determine if it might strike Earth in the next 100 years or so. The vast majority of the objects discovered so far (more than 99 percent) do not seem to pose a threat. On rare occasions Spaceguard finds a NEO that is predicted to swing close by Earth in several decades. Because the procedure for determining future orbits, like all predictions, has only limited precision, one of these objects might actually be on a collision course. So Spaceguard monitors these few NEOs very carefully, gradually improving the accuracy of the predictions of their trajectories.

An asteroid with a diameter of 200 meters would not wreak the planetwide devastation that a one-kilometer-long rock could, but with an explosive force of 600 megatons or so it would still completely obliterate a city should it make even a nearby hit.

Although Spaceguard has found many asteroids of this size, larger telescopes will be required to efficiently detect all the 100,000 smaller but still dangerous asteroids that cross Earth's orbit. Scientists have made a number of proposals to extend the asteroid search down to objects of about 200 meters, but no commitment yet exists. At best, such an augmented survey will not be complete until 15 to 20 years from now.

The Problem of Spin

A MAJOR CHALLENGE for the B612 mission will be maneuvering around the target asteroid, landing on the body and attaching to its surface. In 2000 the NEAR Shoemaker spacecraft successfully maneuvered into orbit around Eros, the second largest of the known near-Earth asteroids, and even managed an impromptu landing on the 34-kilometer-long body. Japan's Hayabusa spacecraft (formerly Muses-C) is now on its way to near-Earth asteroid 1998 SF36 using ion propulsion. Once there it will lightly touch the asteroid's surface several times to pick up samples that will be returned to Earth. But the asteroid tug would be far larger than either of these spacecraft, and it would have to attach itself firmly to the asteroid because the gravitational attraction at the surface of such a body is only a hundred-thousandth of the gravity on Earth. Researchers are considering several concepts for a mechanism to hold the tug to the asteroid's surface, but the final design will most likely depend on the results of upcoming missions that will study the composition and structure of small asteroids.

To speed up or slow down the asteroid, the space tug must keep the direction of thrust parallel to the body's orbital motion. Small asteroids, though, often spin at rates of 10 rotations or more a day. One way to solve this problem would be to stop the rotation before pushing the asteroid. The tug would land on the asteroid's equator (the ring midway between the two poles of the axis of rotation), point its engines horizontally along the equator and fire them until the thrust brought the rotation to a halt.

This method could be risky, however, because most rocky asteroids appear to be porous, low-density "rubble piles," collections of many large and small boul-



SPACEGUARD SURVEY uses telescopes like this one at the White Sands Missile Range in New Mexico.

ders, interspersed with pebbles and smaller grains loosely held together by the body's weak gravity. Although this type of structure could withstand a force of several newtons distributed over two to five square meters of its surface, the same cannot be said for the internal stresses created by slowing down and stopping the body's rotation. It seems highly likely that altering the finely balanced gravitational and centripetal forces associated with asteroid rotation would cause significant and possibly destructive rearrangements—in other words, asteroid quakes.

For this reason, a better alternative might be to allow the asteroid to continue rotating but to torque the spin axis gradually until it is parallel with the

fore precisely deflect the asteroid onto a trajectory that ensures it will not end up in a resonance orbit. This requirement for precision is one of the best arguments for the asteroid-tug concept. The tug provides a carefully controlled maneuver, whereas most of the other deflection schemes yield an approximate, uncontrolled velocity change at best, thereby risking a boomerang scenario.

Protecting Our Planet

THE MISSION we are proposing would cost about \$1 billion—a bit more than half of 1 percent of NASA's expected spending over the next 10 years—provided that off-the-shelf power and propulsion systems are used and a single existing

perhaps even the origins of life. Researchers have already learned a great deal by studying meteorites, the pieces of asteroid debris that survive the fiery plunge through Earth's atmosphere, but a much greater payoff would come from visiting the source of these fragments.

In addition, asteroids are believed to contain large amounts of metals, minerals and water ice. Experts on space exploration claim that taking advantage of these resources could dramatically reduce the cost of future interplanetary flights [see "Tapping the Waters of Space," by John S. Lewis; SCIENTIFIC

Although the use of an asteroid deflection system would be rare, its value would be beyond measure.



body's orbital motion and keep it there. With the axis properly aligned, the tug would push the spinning asteroid along its orbit like a pinwheel. For the B612 demonstration mission, we plan to choose an asteroid spinning at about four rotations a day (typical of asteroids this size) and torque its spin axis by five to 10 degrees [see illustration on page 59]. Using 2.5 newtons of thrust applied at either the asteroid's north or south pole, the task would require a couple months of steady torquing. Although this result would clearly demonstrate the capability to maneuver an asteroid, an actual deflection would require many months, and perhaps even years, to properly orient the asteroid and accelerate it in the desired direction.

Another important challenge would be to deflect the asteroid in such a manner that it does not simply return again several years later on a new collision path. Bodies passing close to Earth are often gravitationally deflected into resonance orbits that have periods that are proportional to Earth's period; as a result, the bodies may periodically return to our planet's vicinity. We must there-

launch vehicle can lift the spacecraft. Is this project worth the expense? Although the actual use of an asteroid deflection system would be rare—never in our lifetimes, we hope—its value would be beyond measure. An asteroid collision with Earth would be so potentially devastating that preventing it would be worth almost any cost. By practicing an asteroid deflection, the B612 mission would show whether the asteroid-tug concept is feasible and, if so, how it should be refined in the event of a real impact threat.

The scientific benefits of the demonstration mission would also be significant. Asteroids are remnants of the early solar system and have much to tell us about the formation of the planets and

AMERICAN PRESENTS, Spring 1999]. The B612 mission would vividly show that spacecraft could access these materials; using the same maneuvering and docking techniques developed for the asteroid tug, other vehicles could land on asteroids and begin mining operations. And these efforts may eventually pave the way for a manned mission to a near-Earth asteroid. Indeed, many experts contend that sending astronauts to an asteroid would be quicker, less costly and more worthwhile than a human mission to Mars.

Most important, the B612 demonstration would fulfill NASA's stated mission, "To protect our home planet ... as only NASA can." A better match could hardly be found. SA

MORE TO EXPLORE

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More information about the B612 mission can be found at www.b612foundation.org

New reports on near-Earth objects are available at neo.jpl.nasa.gov/neo/report.html, impact.arc.nasa.gov/ and neo.jpl.nasa.gov/neo/pha.html