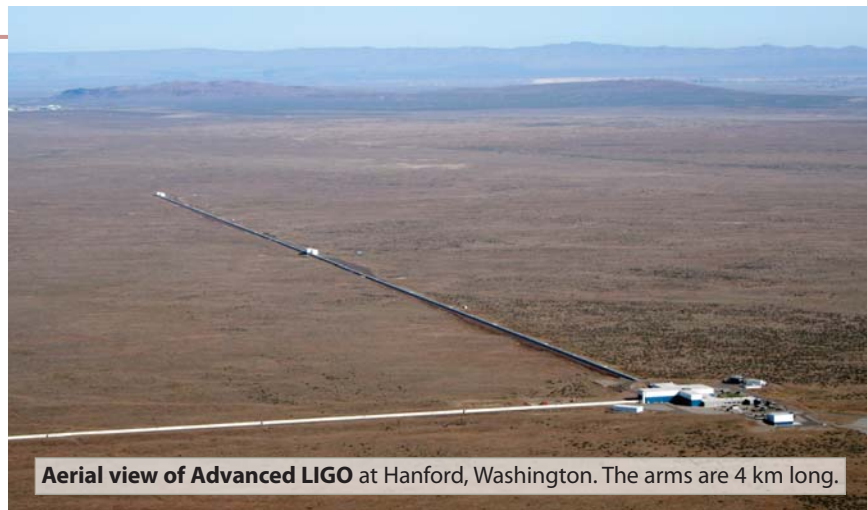


few years, that will seem a little slow.” More-sensitive detectors would also be able to detect lower frequencies, possibly down to a few hertz, which would allow, for instance, probing of intermediate-mass black hole binaries and observing compact binaries for extended periods. “Think minutes to hours,” says Evans. “This could potentially allow us to send alerts to electromagnetic observatories before the coalescence.”

Sensitivity to lower frequencies may also let scientists more precisely estimate binaries’ masses, spins, orientations, and distances, and then calculate cosmic expansion rates and test previously inaccessible predictions of Einstein’s general theory of relativity. Examples, says B. S. Sathyaprakash, a theorist at the UK’s Cardiff University, are the “no-hair” theorem of black holes, which says they are completely described by mass and spin, and interactions of black holes “when they orbit about each other under strong gravity.” Longer term, he adds, low-frequency gravitational waves may be used to measure the equation of state of dark energy. Detection of frequencies below a few hertz requires a space-based detector with vastly longer arms; the European Space Agency is launching *LISA Pathfinder* this fall to test the feasibility of laser interferometry in space.

In Europe, plans for a future ground-



Aerial view of Advanced LIGO at Hanford, Washington. The arms are 4 km long.

LIGO LAB

based system, the Einstein Telescope, are well under way; a conceptual design was completed in 2011. The design calls for three V-shaped interferometers whose arms form an equilateral triangle. The arms would be 10 km long, and the entire system would be underground. “Ground motion changes local gravity,” says Lück, an Einstein Telescope spokesman. “You cannot shield from Newtonian noise, gravity gradient noise. But the environment is more homogeneous underground. Simulations show that [a depth of] 100 m to 200 m gives good improvement.”

The Einstein Telescope would use three 500-W lasers, resonantly built up to 3 MW, and its multiple interferometers with 60° arm separation would

allow scientists to extract the polarization of gravitational waves. For some cosmic sources, localization would require more than one third-generation detector; it may also be possible to use the Einstein Telescope embedded in an upgraded network of second-generation detectors.

In the US, talk about a successor to Advanced LIGO is just starting. The design being tossed around for the Cosmic Explorer is a surface interferometer with 40-km-long arms.

It’s too soon to go looking for the roughly \$1 billion that a third-generation gravitational-wave observatory would likely cost. First, scientists agree, gravitational waves have to be detected.

Toni Feder

How many asteroids are out there, exactly?

The effort to find objects that might threaten Earth is far from complete, and NASA admits it won’t meet a 2020 congressional deadline to find the bigger ones.

Two years ago, without warning, a house-sized meteor exploded 30 km above Chelyabinsk, Russia; it produced a shock wave that damaged thousands of buildings and injured around 1500 people (see the article by David Kring and Mark Boslough, *PHYSICS TODAY*, September 2014, page 32). It was a startling reminder of the sea of asteroids and other near-Earth objects (NEOs) through which our planet moves.

Of the nearly 13 000 NEOs that have been cataloged, 1600 are considered potentially hazardous in that their paths might cross Earth’s orbit. Scientists have estimated that around 22 500 NEOs are larger than 100 m in diameter. But the Minor Planet Center, the central registry of NEOs, located at the Smithsonian Astrophysical Observatory, has cataloged just 7840 of them, says the

center’s acting deputy director José Luis Galache. The good news is that astronomers have located more than 90% of the objects larger than 1 km, including 200 potentially hazardous ones. None of those have been determined to pose a threat to Earth for at least the next 100 years or so, says Jim Green, director of planetary science at NASA.

Of greater concern, perhaps, is that fewer than 1% of an estimated 1 million NEOs larger than 20 m have been spotted, says Gerhard Drolshagen, co-manager of the European Space Agency’s (ESA’s) near-Earth objects division. Relatively small objects can still wreak havoc: The impact from an 80-m asteroid would produce a crater the size of Washington, DC, says Green. The 1908 meteor that exploded in the Tunguska event over Siberia, flattening 80 million



The asteroid 433 Eros, 17 km across, is the second largest known near-Earth object, after 1036 Ganymed.

NASA

trees in a 2000-km² area, was an estimated 60 m in diameter. And the Chelyabinsk meteor was calculated to be 17–20 m.

Scientists estimate that another Tunguska-sized event could occur once every 800–1200 years, says Bruce Betts, director of science and technology at the Planetary Society, a US-based nonprofit. “But you don’t know if the next one will be tomorrow or in 5000 years,” he notes. Lesser events like Chelyabinsk—the largest known since Tunguska—have occurred on the order of tens of years apart.

A 10-km asteroid—the size of the one that may have caused the dinosaurs’ extinction—impacts Earth perhaps once in tens of millions of years, says Betts. Some asteroids 10 km or larger, including 1036 Ganymed at 33 km and 433 Eros at 17 km, are among the NEOs. None are deemed a threat to Earth. But “things change,” Green warns. “Things collide out there.” He says various solar effects can make slight changes in NEOs’ orbits. New objects are pitched into near-Earth orbit all the time as the gravitational interplay between Mars and Jupiter interacts with the 300 000 asteroids in the main asteroid belt. Green adds, “The solar system we live in is dangerous. The knowledge that we have tells us that tons of asteroidal material falls onto the Earth every day.”

Lawmakers’ demands

It’s no secret that NASA won’t be able to meet a 2005 congressional directive to find 90% of NEOs larger than 140 m by 2020. The problem, says Green, is that lawmakers have failed to back up their mandate with the necessary appropriations. For years NASA’s NEO operations struggled by on budgets in the \$4 million to \$5 million range. In recent years though, the budget has risen steadily by \$10 million a year, to \$40 million in fiscal year 2015, and the Obama administration has requested \$50 million for FY 2016. As a result, the number of newly discovered NEOs has gone from 893 in FY 2011 to 1472 last year.

In the hunt for NEOs, NASA buys time on ground-based telescopes, mainly a pair of instruments operated by MIT at the US Army’s White Sands Missile Range and telescopes operated by the University of Arizona’s Catalina Sky Survey. The agency, working with the University of Hawaii and the Air Force Research Laboratory at Mount Haleakala, Maui, is also using the wide-field Panoramic Survey Telescope and Rapid Response System.

The increase in funding has paid for more time at the Arecibo Observatory, where NASA has its own transmitter and where some 40–80 new NEOs are

discovered each year. The radio telescope also can be used as a radar to provide information on nearby NEOs regarding spin period, size, and, in many cases, shape. If asteroids are close enough, “we can even see boulders on them and verify that they are rubble piles,” Green says, referring to those that have accrued material over millions of years.

In 2013 NASA repurposed its *Wide-field Infrared Survey Explorer* (WISE) satellite from its original astronomical surveying mission to the hunt for NEOs. Renamed *NEOWISE*, the spacecraft will operate for another year be-

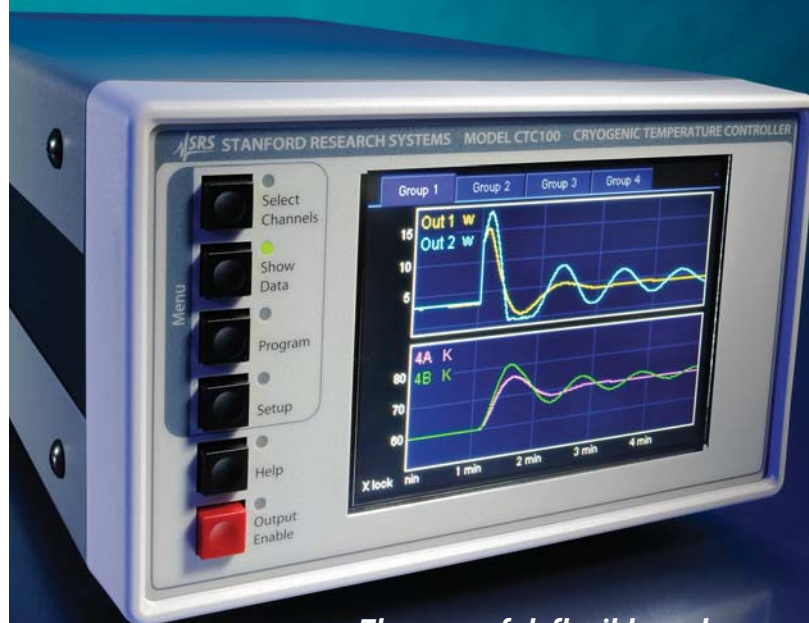
fore running out of fuel and reentering the atmosphere (see *PHYSICS TODAY*, March 2015, page 19). Throughout its astrophysics mission, the satellite had picked up incidental asteroid sightings valued by NEO catalogers.

But *NEOWISE* wasn’t built for an asteroid mission; assembling a full view of the sky takes it six months. “We believe a dedicated mission is the way to go. It would enable us to survey and obtain the position and number of NEOs of interest much quicker,” says Green. However, no funding has been made available for such a satellite.

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the *Hubble*? That would be like looking for a spot on an elephant with a straw," says Green. "You want to see the whole elephant; then you zero in on that spot and watch it move."

European efforts

Complementing NASA's efforts, ESA's 1-m Optical Ground Station telescope at Tenerife's Teide Observatory performs follow-up observations to discern NEO orbits. The ESA-funded Near Earth Objects Dynamic Site (<http://newton.dm.unipi.it/neodys/>), located in Pisa, Italy, is one of two centers worldwide devoted to calculating the orbits and risks to Earth of known NEOs; the other is at NASA's Jet Propulsion Laboratory.

ESA recently secured funding for a 1-m ground telescope optimized to

search for asteroids and having a very wide field of view, says Drolshagen. Ultimately, the agency would like to have four such instruments to survey the complete sky every night.

Help may come from the private sector. Planetary Resources is one of two US companies planning to mine near-Earth asteroids for water and minerals in the years ahead. In July the company launched its first spacecraft from the International Space Station on a flight to test the computers, control and power systems, radios, and other components that will be needed for prospecting. Its second satellite, scheduled for launch later this year, will put a telescope into orbit.

"We are going out in Earth orbit and doing something you can't do even with

the largest telescope on the largest mountain on the planet: To look at asteroids on the sunlit side of the Earth," says Planetary Resources president Chris Lewicki.

"Statistically, we should have discovered 1000 or so Atira asteroids [those whose orbits lie entirely within Earth's], when you compare them to other categories. In reality, the number is now 14 or 15," Lewicki says. The Chelyabinsk meteor, he notes, arrived on Earth's daytime side, "and there is no system in place that could have seen that coming."

Through its two-year-old "grand challenge" program, NASA is enlisting help from and offering prizes to citizen-scientists from around the world. One programmer received a prize of \$55 000 for improving the performance of an

Physics whiz kids converge in India

For a week in July, 382 high school students from 83 countries competed in this year's International Physics Olympiad (IPhO). The event took place in Mumbai, India.

The top scorer was Taehyoung Kim of South Korea, who also had the best marks on the theoretical part of the competition; the best experimental score was earned by his teammate Sol Kim. A total of 38 gold medals were awarded to competitors from 16 countries (lower photo). The only country for which all five team members won golds was China. The teams from Russia, South Korea, Taiwan, and the US each took home four golds and a silver.

Earning gold medals on the US team (top photo) were Zachary Bogorad (front left) of Solon, Ohio; Adam Busis (front right) of Silver Spring, Maryland; Kevin Li (second from left) of Princeton Junction, New Jersey; and Saranesh Prembabu (center) of San Ramon, California. Jason Lu (second from right) of Lincolnshire, Illinois, garnered a silver. The American Association of Physics Teachers and the American Institute of Physics are the main sponsors of the US team. Ahead of the olympiad, the US competitors flew to Bangkok for five days of training with the team from Thailand. They were invited by Thailand's Institute for the Promotion of Teaching Science and Technology.

This year the theoretical calculations involved photons and

neutrinos from the Sun, the extremum principle in classical and quantum mechanics, and the design of a nuclear reactor. In the experimental part of the competition, students used diffraction to determine geometrical parameters of a helical spring and to calculate the surface tension and viscosity of water. (The problems, solutions, and more about IPhO are at <http://www.ipho2015.in>.)



PAUL STANLEY

When not busy with exams, students visited a research institute and a car and truck manufacturing plant, went on a walking tour of South Mumbai, and saw other local sights.

The olympiad in India "was one of the best, if not the best, we have ever had," says IPhO president Hans Jordens. "The problems were interesting and challenging," he says, and "neither cost nor effort were spared to have the competition run well."

Paul Stanley of Beloit College, a coach for the US team, says the team's "strong performance" and the training in Thailand were highlights for the students. "But the real value is meeting peers from around the world. Sometimes the competitors stay in touch for years."

The 2016 International Physics Olympiad will be jointly hosted by Switzerland and Liechtenstein and held in Zürich.

Toni Feder



HOMI BHABHA CENTRE FOR SCIENCE EDUCATION (TIFR)

asteroid detection algorithm by 15%, says Jason Kessler, who heads the program. And a team from Oracle participating in a day-long hackathon converted spreadsheet data entries into a visualization tool (<http://asteroid-explorers.com/mpc>) with multiple filters, at a cost of just \$10 000, Kessler adds.

The Planetary Society offers small grants to astronomers, mainly to track NEOs that have been discovered. "Once you discover an object, you know almost nothing about its orbit," says Betts. "It takes a lot of observing time to get enough information to calculate the orbit and figure out what you really want to know, which is whether it's going to hit Earth."

Planetary defenses

Finding an NEO that's on a collision course with the planet raises the question of what can be done about it. Various concepts for defending Earth have been floated, and they vary according to available warning time. However unlikely it may be, "we actually can prevent this natural disaster, which separates it from any other natural disaster," Betts says. "We feel a responsibility to people of Earth to try and prevent something we can prevent through more research and planning."

ESA, NASA, the German Aerospace Center, the Côte d'Azur Observatory, and the Applied Physics Laboratory of the Johns Hopkins University are planning a mission to the binary asteroid 65803 Didymos in 2022, when it will pass its closest to Earth, 0.07 AU

Paths of the known potentially hazardous near-Earth objects larger than 140 m as of early 2013. None of the 1400 objects are considered a threat over the next 100 years.

(10.5 million kilometers). Two spacecraft would be involved: One would take measurements and characterize the target object and then observe the second spacecraft smash into it. The force of the collision would likely deflect the orbits of the asteroid pair.

Another deflection approach is to paint the asteroid. "If you change reflectivity and absorption, you can actually use that to move [the NEO] in a specific direction," notes Green. In a concept known as the gravity tractor, a spacecraft would pluck a boulder weighing tens of tons from the surface of an NEO. The gravitational force exerted by the spacecraft's mass as it moves away would tug the NEO out of its threatening trajectory. NASA's asteroid redirect mission vehicle would be ideal

for that role, he says (see PHYSICS TODAY, August 2015, page 29).

Vaporizing some of an NEO's surface with ion beams or a laser also may provide the necessary nudge. The Planetary Society has been funding research on a solar-powered laser by a team at the University of Strathclyde and the University of Glasgow.

Many of the same techniques might be used to prevent collisions of manmade satellites in Earth orbit, notes Drolshagen. But each would require years of advance warning to succeed. If little time is available, there is the nuclear option. A surface explosion likely would fragment

the NEO, and the x rays from an above-surface detonation would vaporize much of the asteroid's surface and deflect its path, he says.

But Earth would essentially be defenseless if the warning time were just a few weeks or months, and the only option then would be evacuation of the expected impact area, Betts says.

Everyone agrees that the risk of a catastrophic hit is slight and that there is a fine line between educating the public and creating panic. "The public doesn't understand probabilities, for example, and it doesn't understand kinetic energy levels," notes Drolshagen. There are two parts to public education, says Betts. "One is to make people aware of the threat so it's not laughable. The other part is to convey to people that the danger at any given point is low. Clearly, it can go wrong and be done wrong."

David Kramer



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