

to its five-year Arctic Research Plan. Last March President Barack Obama and Canadian prime minister Justin Trudeau jointly pledged “to more broadly and respectfully include indigenous science and traditional knowledge” on several science and policy fronts, including “advancing our understanding of climate change.” And in September, at a White House ministerial meeting, the US, the European Union, and 23 other governments committed to expanding international collaboration on Arctic science—and to doing so in partnership with the Arctic’s indigenous peoples.

Martin Jeffries, executive director of the Interagency Arctic Research Policy Committee, points to several tangible gains that emerged from the ministerial gathering, including the planned expansion to Canada and Finland of the Environmental Protection Agency’s Local Environmental Observer Network, an online forum in which scientists and community members discuss unusual



THE SIKU-INUIT-HILA PROJECT was a 2006–13 collaborative study of sea ice that teamed scientists with members of Inuit communities in the US, Canada, and Greenland. Here, team members install an ice-thickness monitoring station. (Image courtesy of Shari Gearheard.)

environmental occurrences. Jeffries says the most important development, however, may have come before the meeting was gavelled in: “The day before, we had an afternoon listening session where about 40 senior leaders from the federal government sat down with about 40 leaders of Alaska native and international indigenous peoples organizations to listen to their concerns, their needs,

and how they’d like to be involved in Arctic science.”

That’s progress, says Pew’s Huntington. But he nevertheless sees a gap between the rhetoric and actual investment. “It’s terrific that it’s getting that high profile,” he says. “But it still feels at times like an uphill battle to get beyond the pilot project and workshop stages.”

Ashley G. Smart

Effort in asteroid defense under way despite funding constraints

A US interagency program is refining methods of deflecting asteroids as it works toward finding tens of thousands of undetected near-Earth objects.

In 2013 a meteor estimated to be 17 m in diameter exploded with the energy of a 450 kt nuclear weapon in the sky 23 km above the Russian city of Chelyabinsk. Although no lives were lost, more than 1600 people were injured, mostly from flying glass shattered by the shock wave. Regional hospitals were overwhelmed.

That was before Russia annexed the Crimea and relations with the US soured. Collaborations between US and Russian national laboratories dating to the immediate post-Cold War period were ongoing. It was natural for Russian lab directors to seek help from their US counterparts to mitigate a future asteroid strike, says Don Cook, who as the director of defense programs and deputy administrator of the Department of Energy’s National Nuclear Security Administration (NNSA) oversaw the US

nuclear weapons labs and arranged their participation in the bilateral research effort.

In seeking interagency approval for that effort, Cook met some resistance from staff at the National Security Council. The suspicion was that the NNSA labs might use such a program as a pretext to resume nuclear testing, in the event that an existing weapon couldn’t be used against an asteroid. Ultimately, the skeptics at the security council were mollified when the NNSA and NASA signed a memorandum of understanding to cooperate with each other on what has become known as planetary defense, with NASA designated the lead agency.

The program has grown even after collaborations with Russia were terminated in 2014. Today, scientists and engineers at NASA work on planetary defense with counterparts at the NNSA’s

Lawrence Livermore, Los Alamos, and Sandia National Laboratories.

NASA and its contractors continue to discover near-Earth objects (NEOs)—comets and asteroids that have perihelions of 1.3 astronomical units or less—at a rate of a few per day. As of January, approximately 15 000 asteroids and 107 comets have been uncovered and have had their orbits calculated, according to NASA’s near-Earth asteroid survey. Of those, around 1700 are considered potentially hazardous, meaning their orbits pass within 8 million km (1250 Earth radii) of Earth. (See *PHYSICS TODAY*, September 2015, page 22.)

The number of NEOs rises steeply with diminishing size. Although NASA long ago met a 1998 commitment to Congress to locate at least 90% of NEOs larger than 1 km, some 3500 NEOs of 300–1000 m diameter predicted to exist remain undetected, nearly as many as the 3855 that have been located. Approximately 14 500 asteroids of 140–300 m are undiscovered; just 2500 of those in that



THE 17 M METEOR that exploded over Chelyabinsk, Russia, in 2013 spurred efforts to find near-Earth asteroids and defend against their hitting Earth.

size range have been cataloged, according to NASA's scorecard. Smaller objects are not as closely tracked; it is estimated that about 15% of objects of 140–300 m and less than 1% of objects 70 m or smaller have been found. Lindley Johnson, who heads the planetary defense coordinating office at NASA, says that “it is reasonable to say that there are well over 10 million in number between 70 and 20 meters in size.” Johnson recalled that the Chelyabinsk object was even smaller than 20 m.

The meteor that exploded over Tunguska, Siberia, in 1908, flattening trees over a 2000 km² area, had an estimated diameter of 60 m. In planetary defense terms, Tunguska was considered a city killer; according to Cook, if such a blast occurred over a populated area, the number of casualties could reach 1 million. Larger objects would devastate an entire region, although the extent of destruction would depend on asteroid composition. The Barringer crater in eastern Arizona, for example, is believed to have been caused by the impact of a 50 m meteor about 50 000 years ago. A relatively rare nickel–iron asteroid, it devastated much of what is now the eastern half of the state.

The asteroid that wiped out the dinosaurs 65 million years ago was estimated to have been about 10 km in size. “When you talk about dinosaur killers, they’re 50 million–60 million years apart,” says Joseph Nuth, a scientist at NASA's Goddard Space Flight Center who spoke at the December meeting of the American Geophysical Union

(AGU). Calculations of the risk of significant NEO strikes change based on the numbers of objects that have been found, says Los Alamos scientist Galen Gisler, another speaker at the meeting. “Fortunately, those [probability] numbers have been going down the last couple decades.” Adds Nuth, “you can do a lot of modeling, but you can be in the right place at the wrong time.”

Johnson says asteroid detection and mitigation in the US currently is being performed by 250 people and has an annual budget of \$50 million. An NNSA spokesperson, who could not provide a specific value for the labs' contribution, said the activity is considered part of their programmatic work.

Although NASA's budget for asteroid mitigation has grown from \$10 million annually before the interagency program began, Johnson says the program

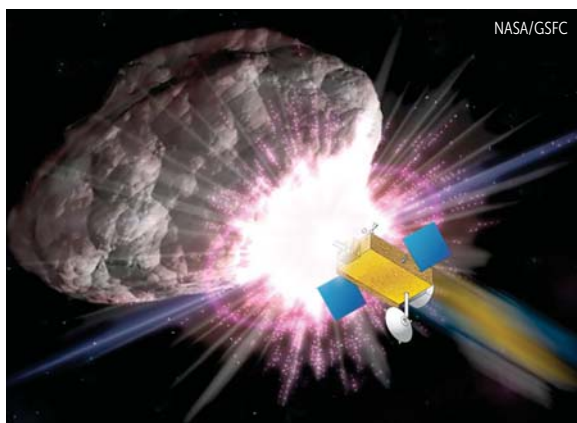
really needs around \$250 million a year. That would include \$150 million–\$200 million annually over five to six years to pay for a space-based IR observatory. At the current rate, ground-based telescopes will take three to four decades to locate all of the 100 m or larger NEOs.

The *Near-Earth Object Camera (NEOCam)* observatory proposed by NASA's Jet Propulsion Laboratory would have cut that “window of vulnerability” to as little as a decade, says Johnson. But *NEOCam* lost out to the two other missions—*Lucy* and *Psyche*—which were given the green light in early January to explore objects in the main asteroid belt.

Preventing catastrophe

As its name implies, planetary defense has to include some method of mitigating an impending strike. Two missions for demonstrating asteroid deflection technologies are already on the drawing board. NASA's *Asteroid Redirect Mission*, proposed for launch in 2020, has a planetary defense component known as gravity tractor. Its primary mission is to pick off a large boulder from an NEO and transport it to lunar orbit, where it would be examined by astronauts. For its secondary mission, the spacecraft would hover near the asteroid to exert a gravitational tug sufficient to alter the NEO's orbit.

Also proposed for a 2020 launch is NASA's *Double Asteroid Redirection Test*, which would evaluate the feasibility of using a kinetic impactor to nudge an asteroid's orbit away from Earth's and would cost about \$250 million, Johnson says. The probe would be



AN ARTIST'S CONCEPTION of a kinetic impactor striking an asteroid at high velocity. The method is one of two main approaches being examined for altering the orbit of an asteroid that is threatening Earth.

directed to crash at 6 km/s into one of the members of the binary asteroid Didymos. The European Space Agency's (ESA's) *Asteroid Impact Mission* would observe the collision and its effect on the binary system. Estimated to cost €250 million (\$260 million), it was not approved by the ESA council of ministers in December. ESA director general Johann-Dietrich Woerner said in a blog post that he remains convinced of the need for the mission and will seek its reconsideration.

Neither NASA mission is currently funded, however. Development money for the redirect mission is included in the fiscal year 2017 budget, which Congress has yet to pass. Proposed in the wake of the Obama administration's decision not to send astronauts to the Moon, the redirect mission is controversial. The Trump administration could cancel it.

The planetary defense program is also weighing the use of a nuclear weapon as a potential last resort. For a kinetic impactor to alter an asteroid's trajectory, at least 10 years' warning of a potential impact would be needed to build the spacecraft and get it to the target. For an asteroid expected to hit Earth with less notice, a larger initial deflection, such as provided by a nuclear detonation, might be needed. Objects larger than 300 m also are likely to require a nuclear deflection, says Livermore physicist Megan Bruck Syal. Modeling shows that an existing nuclear weapon would be able to deflect an NEO of up to 1 km in size, she says. No one has proposed a nuclear demonstration.

In the vacuum of space, a nuclear device wouldn't produce the airblast that's mainly responsible for an explosion's destruction on Earth. For a targeted asteroid, radiation—primarily x rays—from the detonation will vaporize the surface and create a rocket-like blowoff that propels the asteroid in the opposite direction.

Whether the deflection is kinetic or nuclear, Goddard's Nuth said designing, building, and launching a highly reliable spacecraft to intercept an asteroid or comet is likely to take five years. "It's imperative that we reduce our reaction time to less than a year from high certainty of impact to launch," he told reporters at the AGU gathering. He urged that a spacecraft be built so it is available should a threat arise; he estimates the cost to be several hundred million dollars.

Johnson disagrees. He argues that such an interceptor would most likely never be used, would be costly to maintain, and would likely become obsolete as new mitigation technologies are developed in the future. He favors using the available resources to accelerate completion of the asteroid survey.

NNSA contribution

For its part, the NNSA is using its expertise and prodigious computing resources to predict the effects of devices on asteroids. Kevin Greenaugh, the NNSA's assistant deputy administrator for strategic partnership programs, says the modeling helps train young scientists to work on physics problems that are also relevant to the weapons program. Their results on the behavior of materials during impacts are being incorporated into weapons simulations, he says.

Speaking at the AGU meeting, Los Alamos scientist Catherine Plesko said that a kinetic or nuclear device would have to either speed up or slow down the threatening asteroid's orbit. Blowing it up would require more energy and create shrapnel that would have to be tracked. Bennu, a 500 m asteroid discovered in 1999, is the target of NASA's *Origins, Spectral Interpretation, Resource Identification, Security—Regolith Explorer*

(OSIRIS-REX) mission, which will reach the asteroid next year. It has about a 1 in 2000 chance of hitting Earth around 200 years from now, Plesko said. One of the mission's goals is to measure the Yarkovsky effect, the force caused by the emission of heat from the asteroid, which can alter its orbit over time.

Chelyabinsk is about 1600 km from the Kara Sea and 3200 km from the Arabian Sea. Although the meteor that crashed there opened eyes to the threat, an asteroid strike would be most likely to occur somewhere over the three-quarters of Earth that is ocean. Gisler's modeling results show that the wave created by a 300 m or smaller meteor hitting the ocean could reach several hundred meters. But unlike an earthquake-generated tsunami, that wave would dissipate relatively quickly.

Unless the NEO crashed near a coastal city, where its effects would be catastrophic, the most significant impact of an ocean strike would be the injection of huge quantities of water vapor into the stratosphere, where it would not quickly rain out and could affect climate, Gisler says. A Chelyabinsk-like airburst over the ocean would dissipate and have a much weaker impact than a marine strike.

David Kramer

High-energy-density science blooms at NIF

The weapons facility is exploring phenomena found in brown dwarfs, the cores of "super Earths," new phases of carbon, and other extreme environments.

Four years beyond the original deadline for reaching its goal, and more than seven years since it was commissioned, the National Ignition Facility (NIF) has yet to produce fusion energy greater than what's delivered to initiate the laser-driven reaction. But even as scientists at the \$3.5 billion Lawrence Livermore National Laboratory facility continue their quest for ignition, a small but growing band of academic researchers has been harnessing the unmatched compression and other diagnostic capabilities of the 1.8 MJ laser to explore fundamental questions in condensed matter,

astrophysics, planetary science, and other areas (see "NIF may never ignite," DOE admits," June 2016, PHYSICS TODAY online).

"We're trying to grow the community and get more basic science from NIF," says Bruce Remington, program leader for NIF discovery science. The number of shots at NIF devoted to academic research has increased almost fivefold in just two years, to 38 last year, and 8% of NIF's experimental time, some 18 days a year, was set aside for those experiments. Nine projects were selected from the 36 proposals received in last year's solicitation.