Physics Today

Advanced gravitational-wave detectors open their ears

Toni Feder

Citation: Physics Today 68(9), 20 (2015); doi: 10.1063/PT.3.2907
View online: http://dx.doi.org/10.1063/PT.3.2907
View Table of Contents: http://scitation.aip.org/content/aip/magazine/physicstoday/68/9?ver=pdfcov
Published by the AIP Publishing

Advanced gravitational-wave detectors open their ears

Ripples in spacetime and the violent events that cause them may become accessible for study by the end of the decade.


M. PERCIBALLI

Mirrors 35 cm in diameter and 42 kg in mass will be suspended at the ends of each of the 3-km-long arms of the Advanced VIRGO interferometer in Pisa, Italy. It will begin watching for gravitational waves in autumn 2016.

The existence of gravitational waves is not in doubt, although they have yet to be directly detected. Now, with a network of second-generation detectors set to come online, that may soon change. Two US-based detectors that make up the Advanced Laser Interferometer Gravitational-Wave Observatory (Advanced LIGO) begin their first data run this month; Advanced VIRGO in Italy will start up next year; and detectors in Japan and India are poised to follow within a few years.

Gravitational waves manifest as the stretching and scrunching of spacetime. Cataclysmic cosmic events that involve large masses, such as exploding stars or merging neutron stars, "cause disturbances in spacetime," says Sheila Rowan, director of the Institute for Gravitational Research at the University of Glasgow and a member of the Advanced LIGO team. (See the interview with Rowan in the Singularities department of PHYSICS TODAY's online Daily Edition.) "It's a very compelling scientific thing to want to sense these signals."

Reconstructing sources of gravitational waves would allow for tests of Einstein's theory of general relativity and open a window for studying neutron stars and other very compact objects. The gravitational-wave groups will send alerts to dozens of optical, radio, x-ray, and gamma-ray telescopes for follow-up observations.

The second-generation detectors will be 10 times as sensitive in amplitude as the first-generation LIGO and VIRGO. That corresponds to a thousandfold increase in cosmic volume that can be probed; the predicted number of potentially observable coalescing binary neutron stars jumps from 1 in a few decades to 10 a year, give or take an order of magnitude. The frequency threshold is also lower with the new detectors—around 10 Hz, compared with 100 Hz.

Finding the noise

Tuning Advanced LIGO to minimize noise has been going better than expected, and when the interferometers turn on this month they will be able to detect merging binary neutron stars out to a distance of 70 megaparsecs (230 million light-years), says David Reitze, executive director of LIGO Laboratory, which is run jointly by Caltech and MIT. The Advanced LIGO collaboration aims to improve the detectors' sensitivity so that they can pick up signals to 200 Mpc by 2020.

The detectors consist of L-shaped laser interferometers with arms several kilometers long—4 km in the case of LIGO, and 3 km for VIRGO and Japan's Kamioka Gravitational Wave Detector (KAGRA). A gravitational wave emitted by an astrophysical source might shrink or stretch the arm length by a few attometers (1 am = 10^{-18} m, one-thousandth the diameter of a proton). That would be visible from the resulting changes in the interference pattern of the laser light. "Gravitational waves induce relative length changes," says Harald Lück of the Max Planck Institute for Gravitational Physics in Hannover, Germany. "The longer the interferometer arms, the easier it is to detect gravitational waves. It's mostly limited by displacement-like noise."

Many changes went into improving the sensitivity for the second-generation detectors. "There is nothing left of initial LIGO except the vacuum system," Reitze says. "The name of the game is finding all the noises that creep into the interferometer. There are 40 or 50 contributions to the noise that we track." The laser power was increased to 125 W from 5–8 W. That change reduces shot noise. The system now uses larger mirrors—each is about 40 kg, up from 10 kg in initial LIGO—to reduce buffeting from radiation pressure. And the mirrors, which previously were suspended by a single steel wire loop, now hang from four fused-silica fibers. That, explains Lück, lessens the heat-induced "jitter" of mirrors. Improved mirror coatings also reduce thermal noise.

Advanced LIGO and Advanced VIRGO incorporate signal recycling, an additional optical cavity that can amplify the signal and allow the frequency response of the mirrors to be tweaked for specific astrophysical sources. For example, says Reitze, "that would be good for looking for supernovae." But the biggest win for Advanced LIGO, he says, "is from seismic isolation." The new detector measures vibrational noise from the ground and uses feedback to compensate in real time.

All the LIGO changes were done in triplicate, because initial LIGO consisted of three detectors—two in Hanford, Washington, and one in Livingston, Louisiana. The upgrade plan had been to move one of the Hanford detectors to Australia, because bigger separations are better for localizing sources and ruling out spurious signals (see PHYSICS TODAY, December 2010, page 31). But Australia did not come up with money for a vacuum system and housing for the detector. Now the third detector is in storage in Hanford, ready to be sent to India; that plan awaits approval and funding from the Indian government and a final nod from NSF. Construction and five years' operation would cost India about $250 million.

NSF paid the lion's share for the upgrade to Advanced LIGO, some $205 million, and will pay the $40 million in annual running costs for the US sites. A team in Germany contributed lasers, and UK partners supplied the fused-silica mirror suspension systems; those contributions came to about $12 million each for equipment and R&D. Groups in Australia provided about $3 million in systems for positioning and measuring optics to nanometer precision.

Europe and Japan

Improving VIRGO's sensitivity 10-fold required a less extensive upgrade than LIGO's. The suspension system was "already performing at the level of an advanced detector and needed only minor adjustments," says the University of Pisa's Francesco Fidecaro, a former spokesman for VIRGO. "What we did was change the mirrors and the optical system." The main features that were introduced are better mirrors, broader and higher-power laser beams, and signal recycling. The main limitation, he says, is thermal noise, "especially from the coatings of the mirrors."

The sensitivity goal is 145 Mpc, or about 475 million light-years, for the distance at which Advanced VIRGO could detect an average neutron binary merger.

The cost of upgrading to Advanced VIRGO was about €23 million ($25 million). The main partners in the upgrade are France, Italy, and the Netherlands, with Hungary and Poland also contributing. The planned startup in the fall of 2016 is timed to coincide with Advanced LIGO's second run.

Among the second-generation detectors, KAGRA alone is being built underground and will have cryogenic mirrors to battle noise (see PHYSICS TODAY, December 2010, page 34). The total cost is about ¥16.5 billion ($130 million), says the project's principal investigator, Takaaki Kajita of the University of Tokyo's Institute for Cosmic Ray Research. Assuming Japan includes KAGRA in its budget next year, he says, construction will be completed in time to begin a first data run by early 2018.

Gravitating together

The gravitational-wave detectors pick up signals from everywhere, although their orientations mean the sensitivity varies with source direction. To identify the direction from which a signal originates, triangulation is needed. Multiple detectors also help identify false signals. "The more you have, widely separated, the better," says Rowan. The planned network, with five interferometers—two in the US, one in Europe, one in Japan, and one in India—would, she says, "do a pretty good job. Every time you add, the accuracy of the [source's] position gets better."

Indeed, although the projects are separately funded and run, when it comes to data, "We are going to work together," says Fidecaro. "You can make the real physics by identifying the [source] direction in the sky." Advanced LIGO and Advanced VIRGO have a formal arrangement for sharing data, and the parties all foresee expanding to include KAGRA and LIGO-India when those facilities are ready to start up.

Looking ahead

Already, scientists are looking ahead to a third generation of gravitational-wave detectors that would offer even higher detection rates and stronger signals. "Once a month is great when you have never seen anything," says MIT physicist Matthew Evans. "But after a 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-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.

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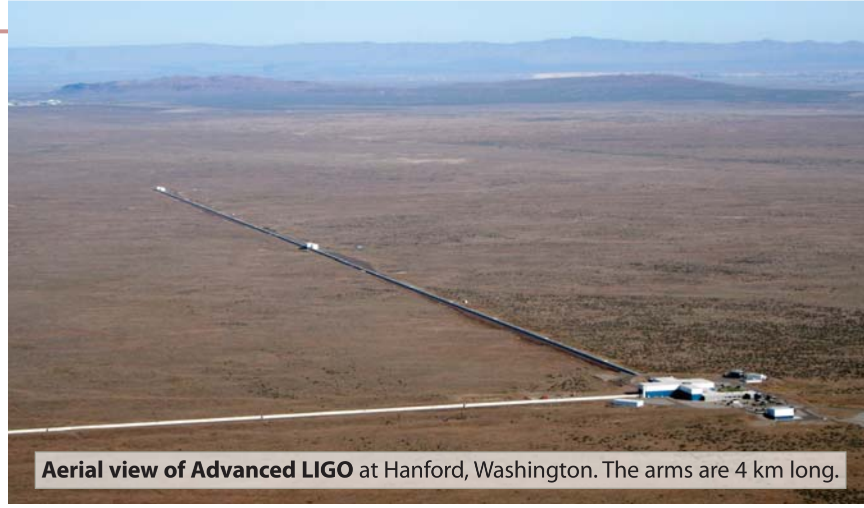

LIGO LAB

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

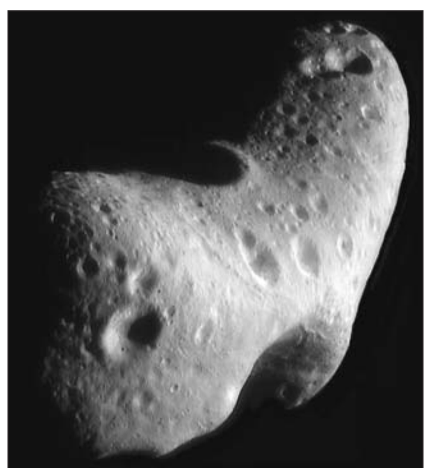
How many asteroids are out there, exactly?

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, comanager 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 trees in a 2000-km^2 area, was an estimated 60 m in diameter. And the Chelyabinsk meteor was calculated to be 17–20 m.


NASA

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