LISA LISTENS TO SPACE

TEXT: AENEAS ROOCH

The largest astronomical observatory is so large that it won't fit on Earth. It's called Lisa, and it will be able to detect when a 2.5-million-kilometer segment of space shrinks by even one atomic diameter. Researchers at the Max Planck Institute for Gravitational Physics in Hanover and Potsdam helped develop the gravitational-wave detector. By observing cosmic waves, they hope to gain an insight into strange processes deep in outer space.

When someone climbs on top of a trampoline, the jumping mat bulges and bobs up and down. Our universe experiences similar distortions known as gravitational waves. They originate from unique processes in the outer reaches of the cosmos and travel through space at the speed of light, squeezing and stretching everything in their way at infinitesimal scales. We cannot see or hear them. Researchers from the Max Planck Society hope to detect particularly long waves to shed light on the shadowy past of our universe, the origin of black holes, and the nature of gravity.

Gravitational waves are invisible distortions of our world. They are difficult to conceptualize, and their existence has been controversial. In 1915, Albert Einstein proposed an idea of how space, time, and gravity are connected – his famous General Theory of Relativity. The formulas he used to describe these relationships lead to the conclusion that certain events in the universe cause compressions and expansions of space and time. Although Einstein himself assumed that these gravitational waves were too weak to be measurable, others at first considered them a theoretical curiosity that did not correspond to any real processes, even though they could be deduced from the equations. A century would pass before gravitational waves were directly measured in 2015.

One situation in which gravitational waves occur is when two black holes orbit each other in a wild, spiral dance until they finally merge. Black holes can be pictured as pressing deep indentations in an imaginary fabric in which space and time are interwoven. As the black holes orbit each other, waves travel through spacetime, dis-

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IMAGE: S. OSSOKINE, A. BUONANNO (MAX PLANCK INSTITUTE FOR GRAVITATIONAL PHYSICS), SIMULATING EXTREME SPACETIMES PROJECT, W. BENGER (AIRBORNE HYDRO MAPPING GMBH)

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Like a whirlwind: Two black holes orbit each other (center of the image), emitting gravitational waves in the process. The image only shows particularly "loud" waves perpendicular to the orbit. One more revolution and the black holes will merge in a fraction of a second. The simulation shows two things: when the black holes were further apart, they emitted weaker gravitational waves (green) than shortly before their merger (orange).

torting the distances between objects – much like jumping on a trampoline causes a shockwave to spread across the entire jumping mat, making it vibrate. Although caused by gigantic masses, the distortions themselves are extremely weak, and get weaker the further away they are from the source. When two black holes with the mass of several Suns unleash gravitational waves in a distant galaxy, they compress the distance between the Earth and the Sun (around 150 million kilometers) by about a millionth of the diameter of a hair.

Extremely precise

Minuscule changes in length like these can only be observed with the help of sophisticated measuring methods, because even an incredibly delicate precision ruler would not be accurate enough. One way to measure gravitational waves is to send a laser beam through a kilometer-long tube, splitting it along the way. Half of the beam continues on its path, while the other half branches off into a perpendicular tube, with both halves reflecting off mirrors at the ends of the tubes. When a gravitational wave passes through our solar system, stretching space in one direction and compressing it along a perpendicular axis, it lengthens the path traveled by the laser beam in the first tube and shortens the path in the second. The light waves in the two tubes no longer oscillate synchronously. When they are superimposed, this discrepancy is revealed in an interference pattern. Detecting slight distortions in space with superimposed laser beams is a complex process. Even the vibrations of a truck rumbling down the next street would render the measurement useless. Nonetheless, the feat was finally accomplished in 2015 by researchers from the LIGO Scientific Collaboration, including several scientists from the Max Planck Institute for Gravitational Physics. However, many gravitational waves still reach us undetected. Just as light consists of electromagnetic waves of different wavelengths, gravitational waves form a spectrum. Laser interferometers on Earth can only detect short-period gravitational waves. Long-period gravitational waves are not yet measurable. First, they are simply too long; it would take a detector larger than the Earth, not dissimilar to giant antennas for capturing long radio waves. Second, the rumbling and crunching of the Earth's interior interferes; the operational noise of our planet drowns out the faint vibrations of space.

PHOTO: THOMAS DAMM

An eye for detail: Guido Müller is a specialist when it comes to detecting extreme events in space that are invisible to traditional telescopes.

As of early 2024, it's official: an extraordinary instrument dubbed the Laser Interferometer Space Antenna, or Lisa, will be launched into space approximately ten years from now on a mission of the European Space Agency (Esa) to measure long-period gravitational waves. Consisting of three satellites spaced roughly 2.5 million kilometers apart, Lisa will orbit the Sun in a triangular formation on an orbit similar to Earth's. To put this in perspective, the satellites will be six times farther apart from each other than the Moon is from the Earth. Each satellite will contain two small, free-floating metal cubes about the size of a package of fresh yeast and weighing around two kilograms apiece. The trio of satellites and the test masses inside them will detect the subtle tremors of space caused by gravitational waves. The gold-platinum alloy on the cubes makes them nearly immune to the effects of magnetic fields, and when solar winds hit the satellites or sunlight bombards them with radiation, the satellites will take precise countermeasures so that the only force acting on the cubes is gravity. When a long gravitational wave passes through our solar system, depending on its origin, it will compress the 2.5-million-kilometer distance by the diameter of an atom or even a bacterium. These tiny changes in length are relatively easy to measure in a lab. In space, however, and at distances like these, the job is much harder.

To take the measurements, the satellites exchange laser beams and perform a series of clever steps before reporting on the position of the cubes relative to each other. This is the only way to reveal whether a gravitational wave momentarily expands or contracts the distance between the free-floating cubes. Three laser beams exchanged in this triangle of satellites form, in a sense, three independent, two-legged laser interferometers that prick up their ears simultaneously.

Unlike with the earthbound laser interferometers, however, the laser beams cannot be superimposed on each other, because they fan out for kilometers as they travel from one satellite to the next, and only a tiny fraction of the beam reaches the neighboring satellite through a plate-sized opening in a telescope. “We’re cutting 30 centimeters out of a ten-kilometer-wide beam of light,” explains Guido Müller, who is now leading the development of the interferometry for LISA as Director at the Max Planck Institute for Gravitational Physics in Hanover. “It’s incredibly challenging to do laser interferometry with this weak laser light.” Once all interferometer signals have been measured with extreme precision and disturbances and fluctuations have been filtered out, they are precisely offset and superimposed in post processing. “But this has little to do with classical interferometry, where two light waves are superimposed and a pattern is revealed,” says Müller. “This is interferometry to the tenth power.” And it takes time to develop such a delicate method of measurement. The idea for it came from Karsten Danzmann, himself a Director at the Max Planck Institute for Gravitational Physics in Hanover more than 30 years ago.

The instrument is being built by Nasa, Esa, and several Esa member states. The Max Planck Institute for Gravitational Physics has taken responsibility for the interferometric detection system and is supporting the mission and Esa on many system design topics. “On paper everything is easy,” says Müller. “But the challenge is to make sure it works later on, in space.” The technology tests in Hanover are therefore designed to be more difficult than live operation is expected to be out in space, where earth tremors and severe temperature fluctuations are not an issue. The Lisa Pathfinder mission, which preceded this one, has already shown that the technology can detect slight changes in length “but as of yet, not over this enormous distance of 2.5 million kilometers,” says Müller. “So, we have a huge responsibility. But unless we’ve overlooked something really stupid, we’ll get it right.”

Exciting mathematics: Alessandra Buonanno’s calculations reveal what astrophysicists need to look for in the data salad.

PHOTO: SVEN DÖRING

Long-period gravitational waves, which Lisa is designed to detect for the first time, originate in part from intense processes in the depths of space. One example is extremely massive black holes, millions of times the mass of our Sun, which orbit each other before merging. Even as single objects, black holes are among the most spectacular phenomena in the universe. They contain an enormous mass compressed into such a tiny space that their gravitational pull traps and swallows everything that gets too close – even light. Some black holes form when stars with masses many times that of the Sun collapse at the end of their lives, squeezing an enormous mass into a tiny space. As extreme as this may be, these stellar black holes are trivial compared to the truly massive black holes that sit at the center of many galaxies and contain millions or even billions of solar masses. How these giant black holes formed, what role they play in the evolution of galaxies, and how they managed to accumulate so much mass is still unknown.

Researchers at the Max Planck Institute for Gravitational Physics in Potsdam hope to distill answers from extraordinarily long gravitational waves. Such waves travel for millions of years before reaching Earth. As a result, they offer researchers a window onto

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SUMMARY

Albert Einstein’s General Theory of Relativity predicts the existence of gravitational waves, which occur when, for example, black holes orbit each other closely or merge.

Gravitational waves from neutron stars or black holes with the mass of heavy stars have relatively short periods and were detected on Earth for the first time in 2015.

Starting in 2035, a trio of satellites called Lisa will measure gravitational waves with longer periods, such as those from massive black holes orbiting each other, in order to explore a previously inaccessible part of the universe.

Researchers hope Lisa will provide a better understanding of how galaxies develop, while also opening a new observational window onto dark matter and dark energy.

an earlier, turbulent stage of the universe. Many billions of years ago, galaxies and their central black holes were increasingly on collision courses, their gravity making them orbit each other. Merging black holes is only one explanation for how black holes in the centers of galaxies become so massive. Some of these massive phenomena grow by about one solar mass per year, when gas flows around them in a disk and falls in. On a cosmological timescale, that can really add up. As a result, long gravitational waves not only provide access to unexplored regions of the universe, but also help us gain a better understanding of how galaxies evolve. What's more, the data will allow researchers to take an inventory of black holes, finding out how many of which type and which mass there are and where they are located.

Lisa will also send other signals to the network, such as when a supermassive black hole swallows an asymmetric partner whose mass is a millionth of its own – for instance, a black hole with the mass of a star or a neutron star. When the mass ratio of an inspiral is this extreme, the merger is prolonged. The light object orbits millions of times on an irregular elliptical and constantly changing orbit around the black hole. Although the gravitational signals emitted by this dance are highly complex, researchers hope to use them to understand how space-time is structured around black holes

Humanity's largest measuring apparatus is going to consist of three satellites that are six times further apart than the Earth and the Moon. The Lisa trio will orbit the Sun and will constantly exchange laser beams (shown in red). When there's a rumble in deep space, say, when two black holes with millions of solar masses merge, a gravitational wave is created. When the wave hits the satellites, it shakes them by a millionth of a hair's breadth. This is measurable.

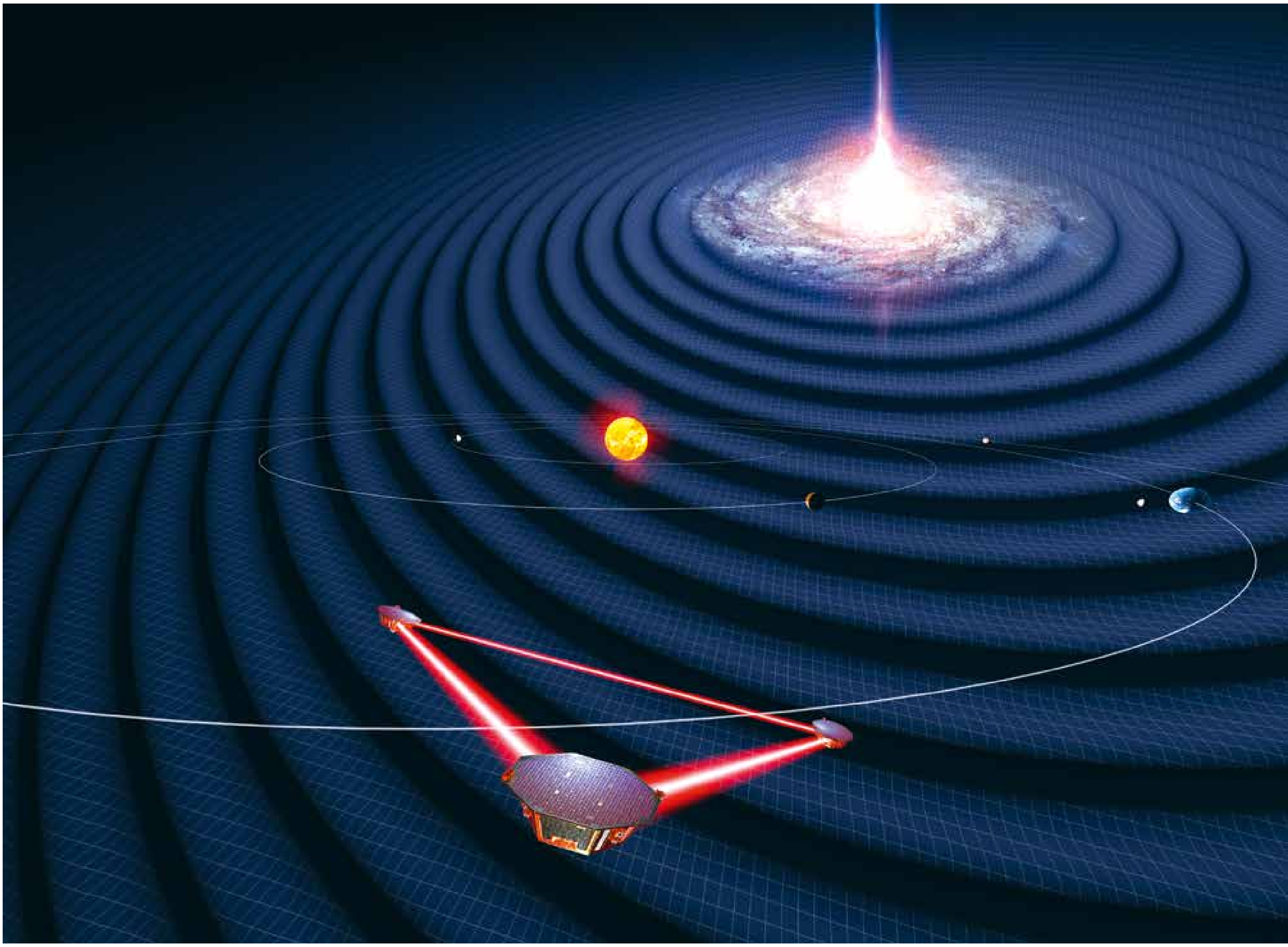

IMAGE: UNIVERSITY OF FLORIDA/SIMON BARKE (CC BY 4.0)

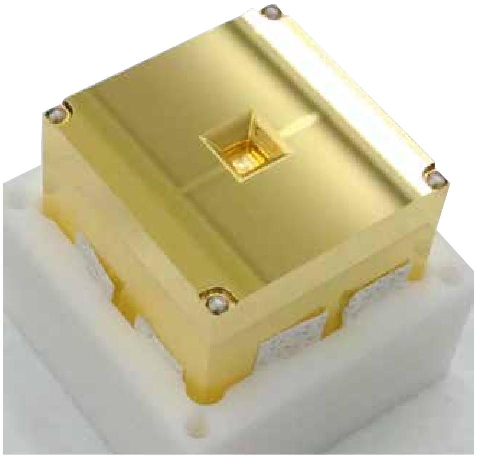

PHOTO: ESA

The sides of this gold and platinum cube measure only 4.6 centimeters. It's the heart of each Lisa satellite. When a gravitational wave shoves this cube just one atom's breadth, a clever laser system raises an alarm.

and to put Einstein's Theory of Relativity to the test.

What Lisa will record is little more than a faint jitter, but it represents the din of countless overlapping waves from various directions and completely different processes. "We don't know how many of these asymmetric partners are out there. We don't know how many pairs of two massive black holes exist. And furthermore, we don't know how many gravitational waves are generated in the depth of space contributing to the stochastic background or random noise," says Alessandra Buonanno, Director at the Max Planck Institute for Gravitational Physics in Potsdam. One major challenge, for example, is the stochastic background in our Milky Way. It is home to countless binary systems of two white dwarfs, which emit long gravitational waves, whose constant murmur drowns out the much quieter signals from the depths of space.

Buonanno and her team hope to isolate individual voices in this chaotic choir to shed light on individual processes in space. "Every source – whether it is a binary system of massive black holes or a massive black hole and a companion with a much smaller mass – produces characteristic gravitational waves. It's like a fingerprint," says Buonanno. "And with the help of theoretical calculations and supercomputers, we can see what exactly these fingerprints look like." Once the researchers are sure which signal comes from which source, they will subtract the pre-calculated vibration directly from the full signal. And once all the processes that cause gravitational waves are known, there should be nothing left of the babble of voices. If not, that's one more problem for astrophysics to solve. "In this way, we can check whether the General Theory of Relativity is completely accurate here, or whether we're encountering a new gravity theory or some physical phenomena that are unknown to us.

Making the invisible measurable

The whole endeavor is mathematically challenging. If the model isn't correct, the signal calculated by the Potsdam researchers might deviate from the actual gravitational waves emitted by a pair of black holes. Not only would this cause the astrophysicists to draw erroneous conclusions from the Lisa data about the pair and its behavior, but it would also produce computational artifacts when the predicted gravitational waves are subtracted from the data stream. The remaining signal could be misinterpreted as a deviation from the General Theory of Relativity. Precise pre-calculation of the vibrations captured by Lisa is therefore crucial to interpreting them correctly. Almost everything in the universe, more than 95 percent of it, emits neither light nor electromagnetic radiation and is treated as dark matter and dark energy. All we know about this invisible and mute proportion of dark matter is that it exists and is subject to gravity. Lisa could detect tiny effects in gravitational waves, which could be attributed to dark matter. The trio of satellites should also be able to take measurements independently of existing telescopes to determine how quickly the universe is expanding and how much dark energy this requires – possibly solving puzzles or posing new ones in the process. "Lisa has what it takes to revolutionize our understanding of the universe," says Buonanno. By unlocking long gravitational waves with Lisa, she and other researchers will open a new observational window onto a dark part of the universe, making the invisible visible – at least on the screens in her lab.

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GLOSSARY

INTERFERENCE
occurs when two wave systems overlap, regardless of whether they are light, water, or sound waves. When the crests and peaks of the waves align, the intensity of the oscillation increases. When the waves are offset by half a wavelength, they cancel each other out.

LASER INTERFEROMETRY
is a method of measuring minute changes in distance. When two laser beams with identical wavelengths are superimposed, they create an interference pattern that is characteristic of the path difference of the two waves. This makes it possible to measure minuscule changes in the distance between two laser sources.