BURSTING WITH CURIOSITY!

TEXT: ALEXANDER STIRN

There are bursts in the sky that are far stronger than lightning. They come from the depths of space and, in extreme cases, release as much energy in milliseconds as the Sun does in a year. These fast radio bursts are far enough away that they pose no danger to humanity. Nevertheless, astronomers want to know what causes them. At the Max Planck Institute for Radio Astronomy, research groups led by Laura Spitler and Michael Kramer are getting closer to solving the mystery. James Lough from the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) thinks that spacetime shocks might even be involved.

The burst came, it has to be said, out of the blue. Extremely bright, extremely short, and most of all, extremely unexpected. British astrophysicist Duncan Lorimer and his student David Narkevic spotted it in 2007 while sifting through archived data from Australia's Parkes Radio Telescope. They noticed a signal they could not explain: what was it? A new, previously unknown cosmological phenomenon, a sensation? Or was it a measurement error, a human-made signal recorded by mistake?

Apparently not, because more radio bursts followed—some similar, some different, some even recurring. At first glance, they raised more questions than answers, not even offering clues to a possible source. The astronomical detective work began. Today, nearly two decades later, many of these questions have been answered, though by no means all. New telescopes, an eye for detail in physics, and downright forensic curiosity have made it possible. The trail leads to some of the most extreme phenomena in the universe—and may help us understand the cosmos and its mysteries a little better in the future.

The phenomenon is known as fast radio bursts, or FRBs for short. The "fast" refers to the duration of the bursts: The signals, which come from seemingly random positions in the sky, flash for only a few thousandths of a second—far less than the blink of an eye. Yet in that short time, they release, on average, as much energy as our Sun does in several days. Since the discovery of the first FRB nearly 20 years ago, not only have many thousands more been detected, but fast radio bursts have proven to be one of the most enduring mysteries in astronomy.

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ILLUSTRATION: ESO

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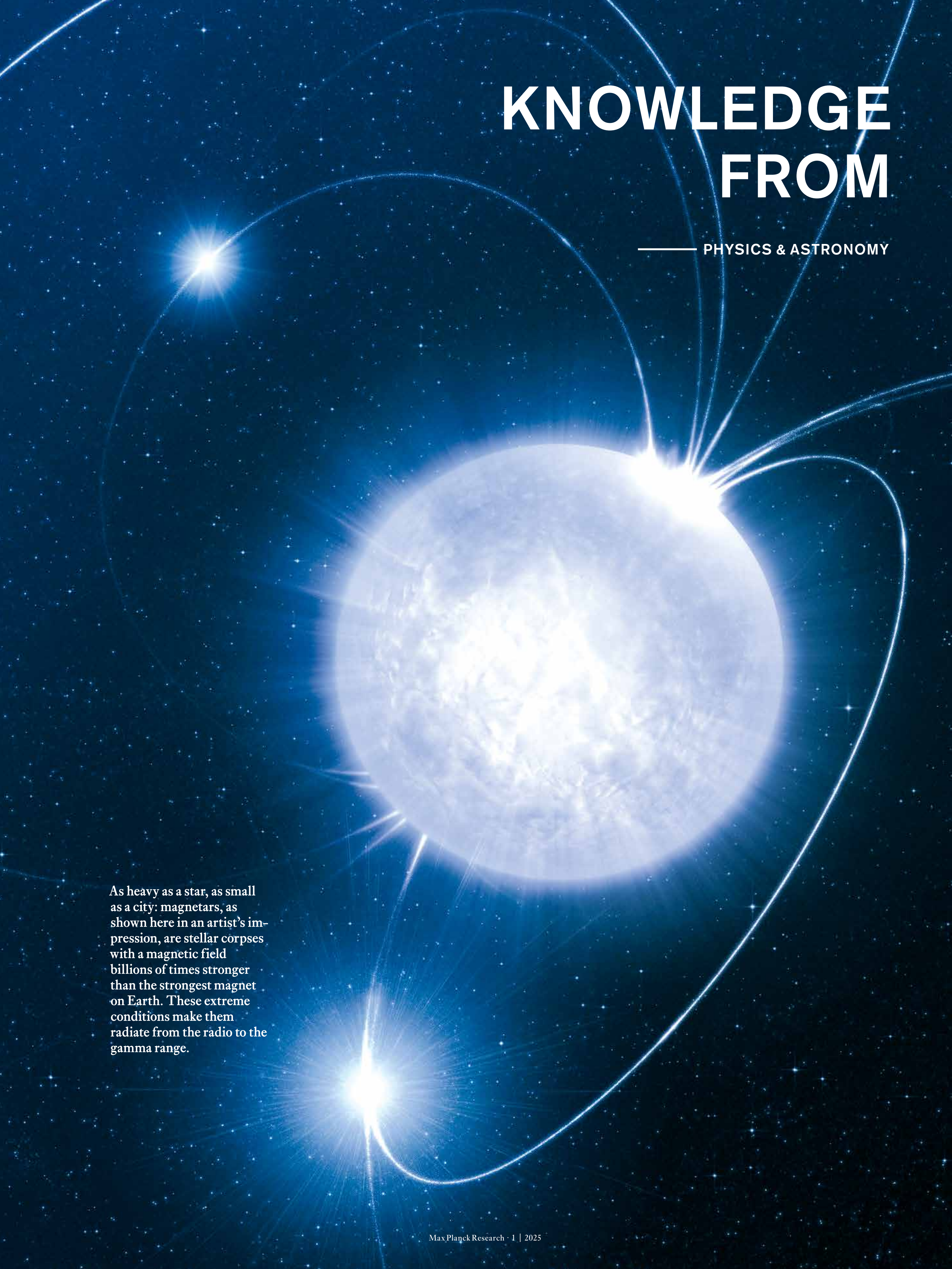


As heavy as a star, as small as a city: magnetars, as shown here in an artist's impression, are stellar corpses with a magnetic field billions of times stronger than the strongest magnet on Earth. These extreme conditions make them radiate from the radio to the gamma range.

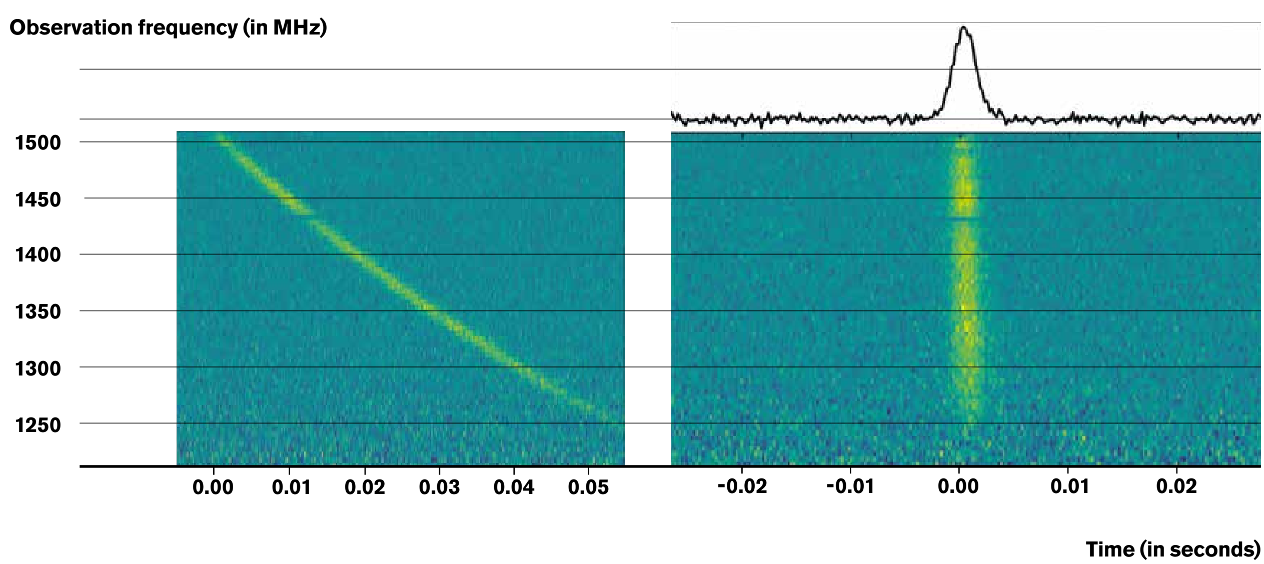
"There were times when we had more theories about the origin of FRBs than FRBs themselves," says Michael Kramer, Director at the Max Planck Institute for Radio Astronomy in Bonn. Evaporating black holes were discussed, as well as exploding stars and oscillating cosmic strings—defects in space that have only existed in highly speculative theories. Even extraterrestrial civilizations were suspected. Or was it human radio signals, mobile phones, or even the microwave in the Parkes Telescope kitchen? "For a long time, it was actually unclear whether the radio bursts were a natural signal or a human-made disturbance," says Kramer.

Laura Spitler has shed light on the bursts. The American-born scientist, who has been a Research Group Leader at the Max Planck Institute in Bonn for six years, made a sensational discovery in August 2014. In archive data from the Arecibo Telescope, a radio dish with a diameter of 305 meters in Puerto Rico, Spitler came across a previously undiscovered radio burst; it was the first discovery with a radio telescope other than the Australian Parkes Telescope. "The characteristics of this FRB, as well as the first Lorimer burst, pointed to astrophysical signals, not some strange human-made interference," says Spitler. Humans obviously had nothing to do with the burst, and the microwave at the Parkes Observatory was vindicated.

But Spitler and her team did not stop there. Two years later, they detected ten more bursts coming from the same direction. The first repeat offender among the FRBs had been identified. "The discovery of this repeater, also known as the Spitler burst, was very important because at the time cosmic explosions were the dominant model for explaining FRBs," says Michael Kramer. But when a star explodes, it can hardly explode ten more times and produce a radio burst each time. So what was the cause of this fast, bright phenomena?

Recurring Extreme Radio Pulses

Although the pulses are short and come from deep space, they can still reveal a lot about their source. Researchers just have to look closely and apply the laws of physics. This is because many properties are etched into the radio bursts—almost like fingerprints. As electromagnetic signals travel through the universe, they inevitably react with and are slowed down by the charged particles that exist even in the supposed vacuum of space. Radio waves at lower frequencies reach radio telescopes with a greater delay than waves travelling at higher frequencies. The stronger this effect, referred to in physics as dispersion, the greater the distance of the astronomical source. The Spitler burst, officially known as FRB 121102, is, according to independent measurements, a good 3 billion light-years away from Earth, placing it outside our own galaxy, the Milky



The Spitler burst FRB 121102 as captured by the 100-meter radio telescope in Effelsberg in 2017. The pulse lasted only a few milliseconds, but stretched like chewing gum across the radio frequency spectrum. On its journey through space, the light reacts with charged particles and is delayed towards low frequencies. On the right, this effect has been calculated.

IMAGE: M CRUCES, L G SPITLER, ET. AL., REPEATING BEHAVIOUR OF FRB 121102: PERIODICITY, WAITING TIMES, AND ENERGY DISTRIBUTION, MNRAS 500, ISSUE 1, JANUARY 2021, PAGES 448–463

Way. This is evidence that the signal from the repeater is coming from deep space.

Because FRB 121102 keeps revealing its location through recurrent bursts, other observatories—including a network of telescopes spread across most of the globe—have been able to point to the area of origin. When telescopes that are far apart are linked together, they can image objects in great detail. This made it possible to pinpoint the origin of the radio bursts. "This was the first time that an FRB could be localized," says Laura Spitler, "and not just in a galaxy, but in a very dynamic region within the galaxy where new stars are forming."

But what does it all mean? These are still mere clues, but they point to a suspect that is one of the most extreme phenomena in the galactic zoo, which is not short of surprises: a magnetar. When a young star, about 10 or 20 times the mass of our sun, breathes its last in a supernova explosion, the core collapses at the same time. It contracts so much that almost all the atoms are crushed. What remains is a pile of neutrons, electrically neutral particles. The entire mass of this neutron star and large parts of the original stellar magnetic field are concentrated in a sphere about 20 kilometers in diameter. If you could put a teaspoon of this matter on a terrestrial scale, the device would read more than 100 million tonnes.

But it can get even more extreme. Some neutron stars have unusually strong magnetic fields. Whether this strong field was present in the original stars or is generated by some kind of dynamo in the collapsing neutron star has not yet been determined. But one thing is clear: the magnetic field is huge. An average magnetar has a magnetic field strength of about 100 billion teslas. To put this in perspective, the Earth's magnetic field in central Europe is 0.00005 teslas, and the strongest magnet ever built by humans reached about 100 teslas (before the magnetic forces became so uncontrollable that it self-destructed). "Magnetars are the most strongly magnetized objects in the universe that we know of," says Max Planck Director Kramer.

SUMMARY

The origin of fast and energetic radio bursts has long been a mystery. Independent measurements suggested a signal from space.

Radio bursts of this kind, which are repeated regularly, suggest magnetars, extremely magnetized stellar corpses with extremely high mass densities. But not all bursts necessarily follow this explanation.

The link between bursts and magnetars can be made directly if a magnetar produces both gravitational waves and a radio burst, both of which could be caused by a starquake.

This magnetic field is also responsible for the fact that magnetars cannot hide in the vastness of the cosmos. Driven by the magnetic field's energy, the celestial bodies, like lighthouses, shoot huge amounts of X-rays and gamma rays into space along narrow cones of light that sweep across the Earth, depending on how the rotating magnetar is oriented in space. A handful of the 30 or so known magnetars also emit radio signals. When astronomers observed a magnetar in the Milky Way in April 2020, they even registered two radio bursts in quick succession. Did a magnetar really produce FRBs? The evidence seems overwhelming: "If you look at this pulse and put other FRB signals next to it, you can't really tell the difference," says Kramer.

Case solved? Michael Kramer is cautious: "While there is certainly some compelling evidence, I would say that the jury is still out." In particular, the relatively low luminosity of the FRB from the Milky Way makes the radio astronomer skeptical. It is only a hundredth, at most a tenth, of the typical energy that has been registered in radio bursts from beyond the Milky Way.

Magnetars Under Suspicion

Kramer calls for more evidence. "For me, a killer argument in favor of magnetars as the trigger would be if we could observe signs of rotation in the source of FRBs." The best suspects would be FRBs that belong to the class of repeaters, i.e. ones that emit regular radio bursts—in the case of the Spitler burst, every 157 days. This is much longer than it takes for magnetars to rotate around their own axis, which is only a few seconds. Perhaps this rotation of the stellar corpse plays less of a role than the gyroscopic motion, or more precisely, the precession, of the axis of rotation itself. This means that it could actually take more than 100 days for the position in the magnetar's magnetic field from which the extremely energetic radio emission originates to fall into the radio telescope's line of sight. It is also conceivable that the magnetar and a giant star orbit around a common center of gravity—possibly once every 157 days—and that the magnetar passes through its companion's massive stellar wind once per orbit. However, the connection between magnetars and FRBs cannot be made conclusively. Not yet. "Until then, magnetars as triggers is a good theory, the best we have," says Kramer. "I think there is a lot of evidence that the repeaters in particular are magnetars." It is still unclear what the individual FRBs are.

But the 300-meter Arecibo Telescope, with which Laura Spitler discovered

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Close cooperation: Marlon Bause, Laura Spitler, Lorena Nicotera (from left) from Spitler's Lise Meitner Group and Ramesh Karuppusamy and Lucia Gebauer Werner from Michael Kramer's Department of Radio Astronomical Fundamental Physics gathered around a model of the 100-meter Effelsberg Telescope.

her FRB a decade ago, is no longer available for such searches. It has partially collapsed after several steel cables broke as a result of poor maintenance. But Kramer is already looking to China, where, at almost the same time, a new, huge radio telescope with a diameter of about 500 meters was put into operation: FAST, the Five-Hundred-Meter Aperture Spherical Radio Telescope. "We work very well with our Chinese colleagues and are happy to do so, and the data from FAST enriches research on both sides," says Kramer. "The telescope has an incredible sensitivity that more than compensates for the loss of Arecibo."

When Starquakes Make Space Tremble

Astronomers also have another powerful tool at the Effelsberg Radio Observatory, south of Bonn. This telescope in the Eifel region, which is operated by the Max Planck Institute in Bonn, has a diameter of 100 meters. Unlike FAST, the dish, which is larger than a soccer field, can be pointed at astronomical objects. A new receiver covering an even wider range of the radio spectrum and a new radio camera that can see much more of the sky than before will be used to unlock more secrets of fast radio bursts in the future.

However, other types of telescopes are also being used. In Sarstedt, south of Hanover, two shafts are cut through the ground between apple trees and farmland, almost at right angles to each other. Each is 600 meters long. The structure is called Geo600. The Max Planck Institute for Gravitational Physics (Albert Einstein Institute) in Hanover wants to use it to detect gravitational waves—vibrations in space and time caused by the movement of gigantic masses. To do so, a laser beam is split, sent into each of the two arms, and reflected at the ends of the shafts. The reflected beams overlap where the arms intersect. When a gravitational wave passes over the Earth, the lengths of the two arms change slightly, but measurably—and so does the overlapping pattern of the laser beams.

FRBs could be related to gravitational waves. According to Einstein's theory, when a magnetar with its enormous mass density begins to oscillate, for example, when the stresses in the neutron star's crust are suddenly released, this triggers gravitational waves. Such a massive starquake would also shake the strong magnetic field of the stellar remnant, which could lead to a short but violent burst of radiation—an FRB. However, when the magnetar at the center of the galaxy suddenly emitted such a burst in April 2020, most gravitational wave detectors were out of operation—due to Covid-19 or scheduled upgrades. But Geo600 continued to record data, says lead scientist James Lough.

Last year, researchers re-analyzed that data. They eliminated the inevitable gravitational noise and looked specifically for waves coming from the Milky Way at the same time as the FRBs. This data could indicate a star-

IMAGE: CHRISTOPH SEELBACH / MPG

quake and oscillations of the magnetar. So far, they have found nothing, but the search continues. “If someone could trigger a few new FRBs in our galaxy, that would be great,” Lough says, laughing.

But the research is evolving. Unlike ten years ago, for Laura Spitler, it is no longer just about detecting FRBs and understanding them as a physical phenomenon. Fast radio bursts are increasingly becoming a means to an end, to solve cosmological puzzles. On their way from the depths of space to receivers on Earth, radio signals travel many billions of lightyears. They pass through the intergalactic medium, a gas located between galaxies. Along with the entire cosmos, this gas is expanding. This expansion, and especially the driving force behind it, is one of cosmology’s great mysteries. Astronomers have therefore coined the term “dark energy” for this mysterious force—and they are pretty much in the dark as to what might be behind it. “But as the radio bursts move through the intergalactic medium, this expansion is burned into their signal,” says Laura Spitler. The big challenge now is to get the information out of the burst. One or two FRBs are not enough. But a large number at different distances—theorists think about 1000 FRBs would be needed—could help.

And then there is all the information that fast radio bursts reveal about their possible sources. “We will never be able to produce matter in laboratories on Earth that is anywhere near as dense as that found in neutron stars or magnetars,” says Michael Kramer. Conditions are so extreme that they are beyond the reach of direct research on Earth. Relativity and gravitational physics would benefit, as would nuclear and plasma physics. “As an astronomer, if I want to understand how the universe itself works, the best way to do that is to look at extreme states and the physics that prevails in them,” says Michael Kramer. “And there are few things more extreme than magnetars.” ←

GLOSSARY

FAST RADIO BURSTS
are rapid radio pulses that last a few milliseconds and are very energetic.

MAGNETARE
are pulsars with extremely strong and well-ordered magnetic fields. Their magnetic field is bipolar, like Earth’s. Pulsars are neutron stars, stellar remnants with the mass of a star and the diameter of a city. They rotate around an axis that is at an angle to the dipole axis of the magnetic field. Charges spiraling along the magnetic field lines emit primarily radio radiation, which is concentrated along the magnetic dipole axis. Like a lighthouse, the cone of radio light sweeps through space and, if the angle is right, across the Earth.