PARKES OBSERVATORY, a radio telescope in Australia, made the first detection of a mysterious brief radio flare from the distant universe.

ASTRONOMY

Flashes in the Night

Astronomers are racing to figure out what causes powerful bursts of radio light in the distant cosmos

By Duncan Lorimer and Maura McLaughlin

ONE DAY IN EARLY 2007 UNDERGRADUATE STUDENT DAVID NARKEVIC came to us with some news. He was a physics major at West Virginia University, where the two of us had just begun our first year as assistant professors. We had tasked him with inspecting archival observations of the Magellanic Clouds—small satellite galaxies of the Milky Way about 200,000 light-years away from Earth. Narkevic had an understated manner, and that day was no exception. “I’ve found something that looks quite interesting,” he said nonchalantly, holding up a graph of a signal that was more than 100 times stronger than the background hiss of the telescope electronics. At first, it seemed that he had identified just what we were looking for: a very small, bright type of star known as a pulsar.

ROBERT B. GOODMAN *Getty Images*

IN BRIEF

A strange burst of radio light from the distant cosmos mystified scientists when they spotted it in 2007.

Astronomers doubted that the flash was celestial until they found similar blasts, dubbed “fast radio bursts.”

A quest is on to discover more of these strange bursts and identify what causes them.

Theories include compact stars, supernovae and even exotic possibilities such as cosmic strings.

These dense, magnetic stars shoot out light in beams that sweep around as they rotate, making the star appear to "pulse" on and off like a lighthouse. Astronomers knew of nearly 2,000 pulsars at the time, and we were leading a hunt for distant and especially bright ones. The search relied on software that one of us (McLaughlin) and her graduate adviser had recently developed to search for individual pulses in radio observations. The code had to account for an effect called pulse dispersion, which works like so: as radio waves travel through space, free electrons floating in the interstellar medium will spread out the waves just like a prism spreads light. The free electrons act as a plasma through which the higher-frequency radio waves travel faster and arrive earlier at the telescope compared with the lower-frequency waves. The farther away a source is from Earth, the more electrons the radio waves will encounter on their journey, resulting in a greater time delay between the high- and low- frequency radio waves. Because we did not know how far away any new pulsars might be, the software scanned the data for signals that might fit many different possible amounts of dispersion, called dispersion measures, or DMs, so that we could be sure to catch pulsars at a range of possible distances.

At the time of Narkevic's discovery, he was analyzing five-year-old observations made by the Parkes radio telescope in Australia, which can survey large areas quickly by observing 13 positions on the sky—called beams—at once. He visually inspected the signals the software detected to weed out the more than 99 percent that were nothing but noise or human-made interference. The signal he found was perplexing not only because it was so bright but because it came from a region of sky a few degrees to the south of the Small Magellanic Cloud, where we would not expect any pulsars associated with the dwarf galaxy. Most surprisingly, the signal had a very high DM—many times higher than we would expect from something in the Milky Way and 50 percent higher than expected even if it were associated with the Small Magellanic Cloud. It suggested that the source was around three billion light-years away, well beyond our local group of galaxies.

If the burst really came from this far, it must have been emitted before dinosaurs roamed Earth. The finite speed of light and the short duration of the signal tell us that it cannot have come from something larger than 10 light-milliseconds across, or about 3,000 kilometers—much smaller than the sun's 1.4-million-kilometer diameter. Although a pulsar could fit within this size restriction, the amount of energy it emitted would have been more than the sun lets out in an entire month and over a billion times more than the brightest pulsar pulses.

What kind of object could be responsible for such a spectacle? Our first priority was to establish whether the pulse could have been produced by human-made interference. Unlike the flashes from pulsars, this one did not appear to repeat; we found only one pulse in the roughly two-hour observation. Still, closer inspection revealed that the arrival times of the pulse's various frequencies exactly followed the expected pattern for interstellar dispersion, a very unlikely coincidence for interference. Additional proof that this burst was astrophysical and not from a human-made radio signal was that it seemed to originate from a single spot on the sky. It showed up brightest in one of the 13 Parkes receiver beams, whereas three others detected it more faintly—precisely what we would expect for a celestial signal. Nearby human interference, in contrast, would typically appear in all 13 beams.

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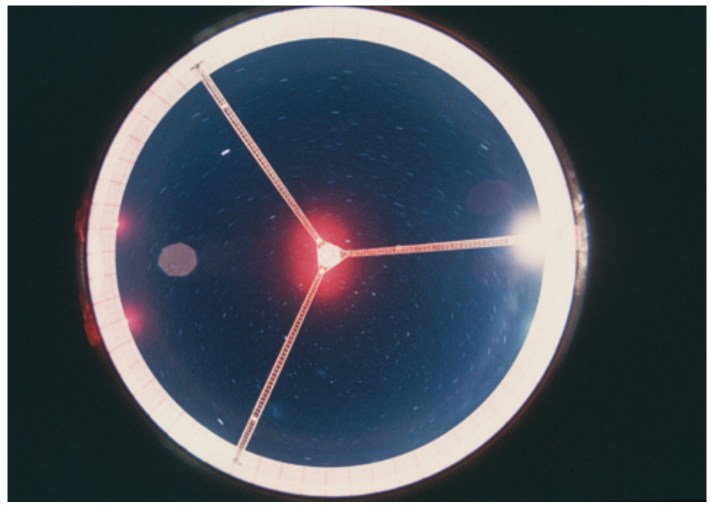


LOOKING UP at the sky from the dish of the Parkes Observatory, astronomers view a field full of stars. After the initial Lorimer burst discovery, Parkes detected several more fast radio bursts.

ROGER RESSMEYER *Getty Images*

It seemed that Narkevic had actually stumbled on something totally new—a type of cosmic signal that would take up more and more of our research focus and puzzle the entire astronomical community. This odd signal, we figured, may not be the only one of its kind. Based on the duration and field of view of the Parkes observation, we estimated that several hundred such bright radio bursts could be going off all over the sky every day, unnoticed. Later in 2007 we published a paper positing that this event was the prototype of a new population of radio sources of unknown origin. We theorized that if we could identify and understand them, we could not only learn about a new type of cosmic event, but we could also estimate their distances through dispersion measurements and use them to do something as grand as map out the large-scale structure of the universe. But first we had to prove the burst was real—a quest that would take many surprising turns and almost end in retreat.

TRUTH OR FICTION?

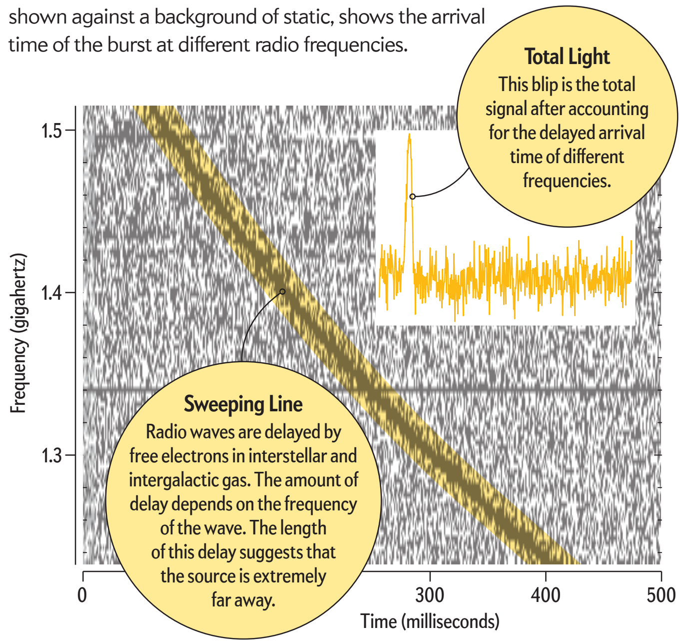
AT FIRST, OTHER RESEARCHERS WERE INTRIGUED by our discovery—quickly nicknamed the "Lorimer burst"—and began proposing explanations for its origin and searching for more like it.

Shortly after our discovery, Matthew Bailes of Swinburne University of Technology in Melbourne and one of the co-authors on our discovery paper, observed the Lorimer burst sky area for 90 hours using the Parkes telescope. But he found no evidence for any other flashes. This follow-up necessarily took place six years after the archival observation that showed the original burst, so it did not rule out the possibility of multiple bursts on timescales of hours or even years around the original observation.

So Bailes and his then doctoral student, Sarah Burke-Spolaor, conducted another search using more archival data from Parkes but in a different area of the sky. In a paper published in 2010 they reported finding 16 events that shared many characteristics with the Lorimer burst. In fact, some had nearly identical DMs and similar durations and pulse shapes. There was, however, a striking difference: every one of these newly discovered bursts appeared in all 13 beams of the Parkes receiver, strongly suggesting that they could not be associated with a source in space. Instead they must have originated from either the ground or the atmosphere—for instance, a lightning strike. To recognize the masquerading nature of these sources, Burke-Spolaor and Bailes dubbed them "perytons" after the mythical winged stag that casts a human shadow.

The Original Burst

This surprising signal, first spotted in 2007 and named "the Lorimer burst," seemed to represent an unknown type of cosmic flash. The inset box shows the brightness of the total radio light over time—the signal was here and gone in a moment. The sweeping line in the larger plot, shown against a background of static, shows the arrival time of the burst at different radio frequencies.



The discovery of perytons made many scientists skeptical of the Lorimer burst. As further radio surveys failed to capture any additional bursts, most astronomers began suspecting that the Lorimer burst was a peryton, too. The number of papers speculating on the nature of the signal started to wane. At one conference in 2011 there was even a show of hands to see what fraction of the audience believed that the Lorimer burst was real. One of us (Lorimer), sitting in the front row, did not dare to look back at the rest of the audience to see the result of the poll!

Four years after the original detection, McLaughlin, along with a postdoc and an undergraduate student, searched a large radio pulsar survey for more bursts. After not finding a single other similar event, even she began to doubt the Lorimer burst. In fact, she and her collaborators wrote a paper that claimed that it was unlikely to be astrophysical after all—a conclusion that feels embarrassing now.

But around this time the field was spectacularly reinvigorated. The first promising event came in 2012, when Evan Keane, now at the Square Kilometer Array Organization, headquartered in Manchester, England, happened on another highly dispersed burst in archival data from Parkes. In the meantime, Bailes had been leading an effort that upgraded the Parkes telescope with state-of-the-art digital instruments, providing unprecedented sensitivity to highly dispersed bursts. His passion paid off: in 2013 researchers found four more bursts with a wide variety of DMs in a new Parkes survey. In the paper that discussed the first results of this survey, led by doctoral student Dan Thornton, who was then at the University of Manchester, the scientists described the events as fast radio bursts (FRBs) in honor of their short durations. Crucially, unlike the perytons, these four bursts were detected in only one beam, making them consistent with an astronomical origin rather than Earth-based interference.

With those discoveries, the astrophysical nature of FRBs became increasingly certain. Then, in a moment of redemption and humor, a 2015 paper by Emily Petroff, then at Swinburne, and her colleagues showed that the Parkes perytons occurred predominantly around lunchtime, when impatient astronomers opened the on-site microwave oven before it was fully turned off. It was a great relief to verify that the timing of neither the Lorimer burst nor the other FRBs overlapped with the lunchtime habits of hungry scientists.

REPEATING FLASHES

SOON, THANKS TO DEDICATED SEARCHES at a number of telescopes by a growing community of researchers, more FRB sightings began popping up. The Green Bank Telescope in West Virginia captured one in a different frequency range of the radio spectrum than the Lorimer burst, providing more evidence that the burst was real and not the product of some peculiarity of the receivers tuned to the original frequency band.

The plot thickened in 2016, when a team led by Laura Spitler

SOURCE: DUNCAN LORIMER

Graphic by Amanda Montañez

of the Max Planck Institute for Radio Astronomy in Bonn, Germany, reported detecting repeated flashes from a burst that had originally been seen in data taken in 2012 at the Arecibo Observatory in Puerto Rico. Until then, astronomers had generally concluded that these were one-off events. But some three years after the original discovery, known as FRB 121102, Spitler and her colleagues saw 10 additional bursts. The arrival times of these bursts do not seem to be periodic, and the radio pulses' precise duration and other characteristics vary.

This discovery triggered multiple campaigns of follow-up observations with radio telescopes worldwide. One of these used the Very Large Array (VLA) in New Mexico, a collection of 27 radio antennas observing in tandem, to regularly search for events on millisecond timescales in the same area of the sky as FRB 121102. This survey had the unique capability to pinpoint radio bursts' locations on the sky several orders of magnitude better than a single radio dish could. After roughly six months of observations, the team—led by Shami Chatterjee of Cornell University—discovered and localized a burst. Soon an even more precise location for this FRB came through the technique of very long baseline interferometry, where signals from multiple telescopes around the world are combined to synthesize a much larger virtual telescope with exquisite resolution on the sky. The finding, led by Benito Marcote of the Joint Institute for VLBI ERIC (JIVE) in the Netherlands and his colleagues, pinpointed the repeated bursts from FRB 121102 with an uncertainty of less than one arc second ($1/3{,}600$ of a degree).

This was the first time astronomers had found such a precise location on the sky for an FRB—which then led scientists to be able to find the source galaxy of the burst. A team led by Shriharsh Tendulkar of McGill University tracked FRB 121102 back to a dwarf galaxy that had a mass roughly 20,000 times as small as the Milky Way and that lay about 20,000 times farther than the most distant known pulsar. These findings established more firmly than ever before that FRBs are powerful and extremely distant phenomena.

SEARCHING FOR SOURCES

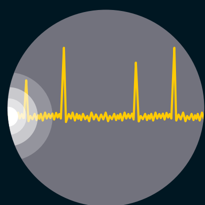
BY NOW WE HAVE ESTABLISHED that FRBs are real cosmic phenomena, but we still have a long way to go to figure out what causes them.

One major question is whether these bursts originate from one-time events—such as supernovae—or whether they come from enduring objects, such as pulsars that periodically emit bright flashes. The case of the repeating burst, FRB 121102, suggests the latter. Although it is the only FRB for which astronomers have detected multiple bursts so far, it is possible that *all* FRBs repeat and that the isolated bursts seen from others represent the very brightest of a distribution of energies. In that case, we would rule out single events and look toward persistent cosmic sources.

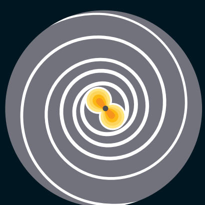
In this category, many scientists favor explanations involving compact stars such as pulsars. These objects result when a large star dies in a supernova, and much of its mass collapses in on itself. The density of this bizarre object becomes so great that even atoms cannot withstand the crush, and their protons and electrons smoosh together to become neutrons. The end product is a star about as wide as Manhattan made almost entirely of neutrons, called a neutron star. These stars rotate extremely quickly and send out light from two poles. The pulsars

Possible Culprits

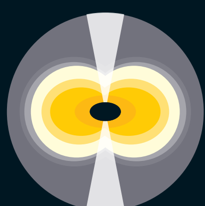
Scientists have several theories for what could be causing the Lorimer burst and similar flashes of radio light dubbed "fast radio bursts" (FRBs). Possibilities range from especially powerful versions of regular astronomical phenomena such as supernovae to exotic theoretical options such as cosmic strings. At least one FRB repeats and thus must be caused by a persistent source—but others could be one-off events.



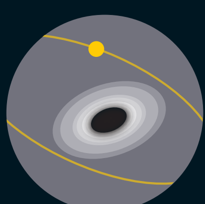
Giant Pulsing Neutron Star
Neutron stars, the dense remnants of dead stars, release light in sweeping beams that appear to pulse on and off as they rotate. A particularly powerful neutron star could be responsible for a fast radio burst.



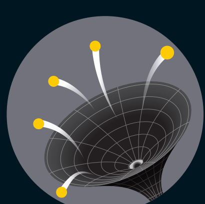
Colliding Neutron Stars
If two neutron stars hit each other, the bang could release a bright flash of light and produce a black hole or perhaps one really big neutron star.



Energetic Supernova
When massive stars die, they collapse in an explosion called a supernova. Perhaps FRBs are especially energetic supernovae.



Magnetar Interaction
Highly magnetized neutron stars, called magnetars, release light powered by their magnetic energy rather than their rotation. If one of these was swirling around a black hole gobbling up matter (called an active galactic nucleus), the interaction could result in an FRB.



Evaporation of a Primordial Black Hole
Some theorists speculate that the big bang could have created primordial black holes sprinkled throughout space. If one of these spontaneously evaporated, a flash of radio light could result.

Cosmic Strings
These defects in spacetime are another exotic possible result of the big bang. If they existed, they could have sparked flashes as they interacted with the plasma that filled the early universe.

Graphic by Nigel Hawtin

we have been discussing occur when these beams are pointed toward Earth and we see light pulsing on and off. The repeating bursts seen from FRB 121102 have properties that are broadly consistent with extremely energetic pulses emitted by a young neutron star. So FRBs could ultimately just be pulsars after all—albeit a rare and especially powerful form.

A closely related idea is the possibility that FRBs come from so-called magnetars: highly magnetized, slowly rotating neutron stars whose emission is powered by their magnetic energy rather than their rotation. One intriguing aspect of the VLA observations of FRB 121102 is the presence of a persistent bright radio light, distinct from the FRB bursts, in the host galaxy. Astronomers have speculated that this radio light is an active galactic nucleus—a supermassive black hole in the process of gobbling up stars and gas—and that the FRB is produced by the interaction between a magnetar and this nucleus.

A variant of this idea is that the repeating bursts are coming from a magnetar but one that is buried in the dense remnant of an explosion from a superluminous supernova (around 10 times more energetic than a typical supernova) that went off a few decades ago. One team of researchers noted that the host galaxy of FRB 121102 is similar to those that harbor a phenomenon known as gamma-ray bursts, which are thought to be connected to extremely young magnetars formed during superluminous supernovae. Very recently, this team measured the magnetic field along the line of sight to FRB 121102. These observations show that, regardless of its source, FRB 121102 must be located in a relatively highly magnetized region such as in a dense supernova remnant or around a supermassive black hole at a galaxy core.

We cannot rule out one-off events just yet, though. Perhaps some bursts repeat and some do not, indicating that different FRBs have a variety of originating sources. In fact, a new study led by Divya Palaniswamy, then at the University of Nevada, Las Vegas, showed that if all FRBs repeat at the rate observed in FRB 121102, then we should have seen multiple events in several other cases. It is therefore perhaps more plausible to consider that some FRBs originate in one-time cataclysmic events. This leaves us with a number of candidate sources.

At the top of the list is the collision of two neutron stars. Such a smash would likely release a powerful blast on contact as the two compact stars merge to form a single gargantuan black hole. A second possibility for a one-time event is the explosion of a particularly energetic supernova.

Theorists have also floated more exotic suggestions. One of these is the idea of cosmic strings—topological defects in space and time theorized to have formed in the early universe. These warps would have raced at light speed through the cosmos, which was then filled with hot plasma, producing sparks as they interacted with the plasma. Although the theory that those sparks are FRBs is not ruled out by the current observations, it is highly speculative. Scientists have also pointed to so-called primordial black holes—small black holes created by the birth of the universe that so far have not been detected. If one of these primordial black holes spontaneously evaporated, it could release radiation that might match an FRB signal. If either of these ideas proved true, the Lorimer burst would be the first observational evidence for these exotic phenomena.

MAPPING THE SKY

After a decade of work, the field of FRB science is now poised to enter a transformative phase thanks to new and updated telescopes. The wide-field-of-view Australian Square Kilometer Array Pathfinder opened in 2012 and soon began finding FRBs. As of this writing, 50 bursts are now known. Existing facilities such as the VLA and the Molonglo radio telescope at the University of Sydney are being refurbished to greatly enhance sensitivity and sky coverage. New and improved radio telescope facilities coming online now—the Canadian Hydrogen Intensity Mapping Experiment and China's Five-hundred-meter Aperture Spherical radio Telescope (FAST), among others—should significantly increase our sample of FRBs and provide a much better understanding of the source population.

Some of the new telescopes can localize FRBs with arc-second precision in real time, greatly enhancing our ability to locate them in the sky. This location information allows us to rapidly follow up with observations in other wavelengths to search for the burst's host galaxies. Even more exciting is that some models for FRBs, such as neutron star mergers, predict that they should also release gravitational waves.

Amazingly, astronomers can now detect these ripples in spacetime at the Laser Interferometer Gravitational Wave Observatory (LIGO), which made the Nobel Prize–winning discovery of gravitational waves for the first time in 2015. With this new technology, there is now a real possibility of jointly detecting light and gravitational waves from these sources. Such a detection would allow for measurements of FRB properties—such as the mass of the burst's source—that are simply not available through other means. We anticipate making major progress in finding and understanding these cosmic messengers very soon.

If we can indeed solve the mystery of the identity and origin of FRBs, we may be able to use these new signals for an ambitious project: to map out the universe. Astronomers are still in the early stages of tracking how matter is spread through space and visualizing the large-scale structures it forms. FRBs could give us a big leg up in our cosmic cartography efforts. They are the only extragalactic sources we know of that have short enough timescales to measure intergalactic dispersion and hence determine how dense matter is along our line of sight. The density in the intergalactic medium is a critical prediction of various models for the large-scale structure of the universe, so information from FRBs could allow us to test which models are correct.

Now that we have a global array of FRB detections all over the sky with independent distance measurements, this work will provide new tests of our fundamental understanding of how the cosmos formed and evolved. Narkevic's initial discovery has turned out to be "quite interesting," indeed. SA

MORE TO EXPLORE

A Bright Millisecond Radio Burst of Extragalactic Origin. D. R. Lorimer et al. in *Science,* Vol. 318, pages 777–780; November 2, 2007.

A Direct Localization of a Fast Radio Burst and Its Host. S. Chatterjee et al. in *Nature,* Vol. 541, pages 58–61; January 5, 2017.

FROM OUR ARCHIVES

Stellar Fireworks. Daniel Kasen; June 2016.

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