Cosmic Interference Patterns

Resolve the Heart of a Radio Burst

BY KIYOSHI MASUI

Fast radio bursts (FRBs) are one of the most captivating enigmas in modern astrophysics: intense, millisecond-long flashes of radio light arriving from galaxies billions of light-years away. Despite over a decade of observations, these phenomena remain poorly understood. What exactly produces them? And how is such powerful radio emission generated?

These two questions—the *what* and the *how*—have driven much of the theoretical and observational effort in FRB research. The *what* concerns the nature of the progenitor: what kind of astrophysical object launches these bursts? The *how* seeks to uncover the physical process responsible for generating the radio waves.

In our recent work [1], my collaborators and I have made a significant advance on the *how*. By observing an interference pattern—known as SCINTILLATION—in the signal from an FRB, alongside a telltale swing in its polarization angle (a hallmark of a rotating source), we've gained a clearer window into the emission process. The evidence points to radio waves being produced directly within the ultra-strong magnetic fields of the progenitor, likely during sudden and violent magnetic reconfiguration events.

Before we tackle the question of how FRBs are produced, it's worth revisiting what we know about their progenitors—and how we found out.

Which neutron stars emit FRBs?

From early on, the brevity of fast radio bursts pointed toward compact objects as their likely sources. FRBs last only a few milliseconds—implying that whatever produces them must be extremely small. To see why, consider the speed of light: in a millisecond, light travels just about 300 kilometers. If an FRB source were significantly larger than this, the travel time of light emitted from different parts of the object would smear out the burst, erasing the sharp temporal signature we observe.

This constraint rules out most astrophysical bodies. The only known objects compact and energetic enough to fit the bill are neutron stars—the collapsed cores of massive stars that have exhausted their nuclear fuel. With no radiation pressure left to counteract gravity, these remnants compress under their own weight to densities comparable to that of atomic nuclei. A neutron star can pack twice the mass of the Sun into a sphere just 20 kilometers across. To put that in perspective: a single thimbleful of neutron star matter would weigh about a billion tons.

Neutron stars can be classified by the energy source that powers their emission. Many are effectively silent: they no longer emit detectable light because they have no active energy reservoir. These neutron stars can still reveal themselves occasionally—most spectacularly when they merge with another compact object. Such mergers are now routinely observed through gravitational waves by detectors like LIGO, and can be accompanied by gamma-ray bursts, linking neutron stars to some of the most energetic events in the universe.

Among the luminous neutron stars, some shine by tapping into their rotational energy. These are the pulsars—rapidly spinning neutron stars that lose energy through magnetic braking. As they rotate, their strong magnetic fields accelerate charged particles and emit beams of radiation. When one of these beams sweeps past Earth, we observe a precisely timed pulse, earning pulsars a reputation as nature's most reliable clocks.

FIGURE 1:
Artist's impression of scintillation in an FRB. A radio flash is generated close to the neutron star, within its magnetic field. The radio waves are lensed by interstellar gas creating a speckle interference pattern. Credit: Daniel Liévano / MIT

FIGURE 2:
The CHIME telescope in British Columbia, Canada. With no moving parts, CHIME points via digital signal processing of the signals coming from its thousand antennas in a method called beamforming. This capability allows it to continually monitor a large swath of the sky and detect FRBs at a rate much greater than other telescopes. Credit: Richard Shaw

Others are powered by their magnetic fields. These are the magnetars, whose fields are the strongest known in the universe. Vast amounts of energy are stored in these fields, which can suddenly reconfigure in violent magnetic reconnection events. These abrupt releases of energy can produce powerful outbursts, making magnetars particularly compelling candidates for the kind of rapid, intense flashes seen in FRBs.

A digital telescope implicates magnetars

Much of the recent progress in understanding FRBs has come from a telescope I helped design and build: the Canadian Hydrogen Intensity Mapping Experiment (CHIME). CHIME is unlike most other radio telescopes—it has no moving parts. Instead of swiveling dishes, it uses a thousand fixed antennas spread across four large cylindrical reflectors. The telescope “points” digitally, using a technique called beamforming to combine signals from its array in real time. This digital steering allows CHIME to observe many directions in the sky simultaneously—an ideal design for detecting rare and unpredictable radio flashes like FRBs.

Since turning on, CHIME has observed over five thousand FRBs. By comparison, all other radio telescopes worldwide have collectively detected fewer than two hundred. This dramatic increase in detection rate has transformed the field and opened the door to new discoveries about the nature of FRBs.

One of the most pivotal came in April 2020: CHIME detected an FRB that was hundreds of thousands of times brighter than usual. The reason? Its source was remarkably nearby—just 30,000 light-years away, within our own Milky Way galaxy. This proximity allowed us to directly associate the burst with an active magnetar, which was simultaneously emitting X-rays.

This detection provided the first direct evidence that magnetars can indeed produce FRBs. It was a decisive “existence proof”: even if not all FRBs come from magnetars—something we still can’t determine, since typical FRB sources lie far beyond the observational reach of X-ray or gamma-ray instruments—some certainly do. That alone marked a major leap forward in understanding the origins of these mysterious cosmic flashes.

Making the radio waves: competing models

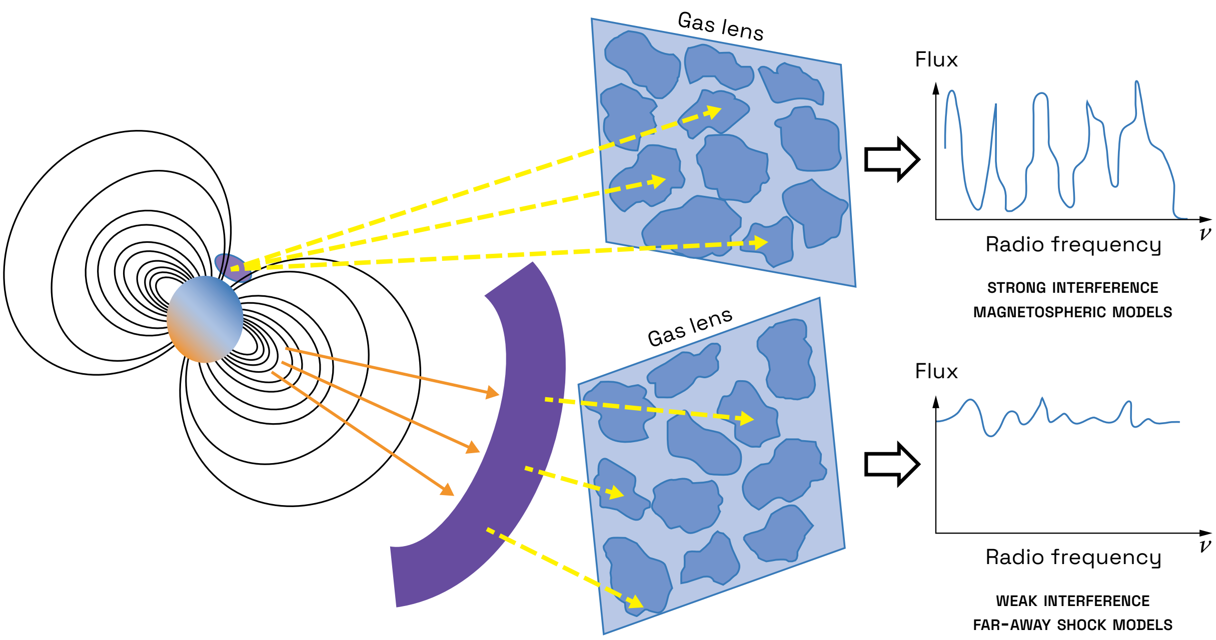
Even as progress has been made in identifying the *progenitors* of fast radio bursts, another profound mystery remains: the emission mechanism. How does nature produce a burst of radio waves so intense, so brief, and so coherent that it can outshine an entire galaxy—for just a millisecond? While there are many detailed theories, most fall into two broad classes.

The first class involves magnetospheric emission, where the radio waves are generated directly within the intense magnetic environment of the neutron star. In these models, a violent magnetic reconfiguration—such as a magnetic reconnection event triggered by a crustal quake—drives nonlinear electromagnetic processes that directly produce coherent radio emission. Because the emission is generated close to the star, where the magnetic field is strongest, these models are tightly linked to the magnetospheric structure and dynamics.

The second class of models envisions a different geometry. Here, an explosive release of energy from the neutron star launches a relativistic shock wave that travels outward through the surrounding medium. As this shock front propagates, it generates radio waves via a synchrotron maser process. Unlike the magnetospheric models, where emission originates near the star's surface, these shock models produce FRBs much farther out—hundreds of thousands of kilometers from the progenitor.

Distinguishing between these emission models would be straightforward—if we could directly image the source. Magnetospheric models predict compact emission near the neutron star, while shock models require a much more extended region. But resolving structures just hundreds of kilometers across at cosmological distances is far beyond current technology. Even the Event Horizon Telescope (EHT), which imaged the shadow of a black hole in M87 by forming an Earth-sized interferometer, could only resolve features spanning billions of kilometers. And M87 is closer than most FRBs; zooming in on an FRB would require a telescope billions of times larger than the EHT.

FIGURE 3:
Schematic of how the presence of interference patterns observed in an FRB spectrum constrains the size of the emission region and thus distinguishes between magnetospheric emission and far-away emission generated by a shock wave. (Adapted from "Constraining the FRB mechanism from scintillation in the host galaxy," Kumar, Pawan; Beniamini, Paz; Gupta, Om; and Cordes, James M.; *Monthly Notices of the Royal Astronomical Society* **527**, 457–470, 2023.)



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Cosmic interference patterns

Fortunately, nature offers another way—scintillation allows us to use clumpy interstellar gas as a giant telescope.

Those trained in physics are likely familiar with the classic double-slit experiment, in which light travels along two distinct paths and produces an interference pattern of alternating bright and dark fringes. But this effect doesn't occur for just any light source. To produce a clear interference pattern, the light passing through each slit must be coherent—its wave phases perfectly correlated from one path to the other.

There are two ways to satisfy this condition. One is to use a coherent light source, like a laser. The other is to use a source that is small and distant enough that it appears unresolved by the slits, effectively behaving as a point source. In that case, the path-length difference between the slits and the detector remains well-defined, allowing coherent interference to occur. This means that the mere presence of an interference pattern tells us something important: it implies the source is sufficiently compact in angular size.

We apply this same principle to determine the size of the FRB emission region using scintillation. The diffuse gas that fills galaxies is inhomogeneous and has a refractive index for radio waves. As FRBs travel through this clumpy gas, it acts like a vast, irregular lens, bending the radio waves so that the signal reaches Earth along thousands of distinct paths—paths that can be separated by billions of kilometers. If the FRB emission is sufficiently small and distant, these many paths remain coherent with one another and interfere just as in the two-slit experiment. In this way, the interstellar gas acts as an interferometer with a scale of billions of kilometers.

With so many disorganized paths, the interference pattern produced by scintillation resembles a random speckle pattern, like those seen when a laser illuminates a rough surface. If we could project this pattern onto a screen, it would span an enormous area—far too large to observe directly. Instead, we detect the interference through radio spectroscopy, where the speckle pattern manifests as a random variation in brightness across different frequencies—a distinctive signature of constructive and destructive interference.

This pattern has a characteristic frequency scale—the typical width of features in the spectrum—which encodes information about the geometry of the lensing gas. And crucially, the mere presence of such a pattern tells us that the source must be compact enough to maintain coherence across these paths.

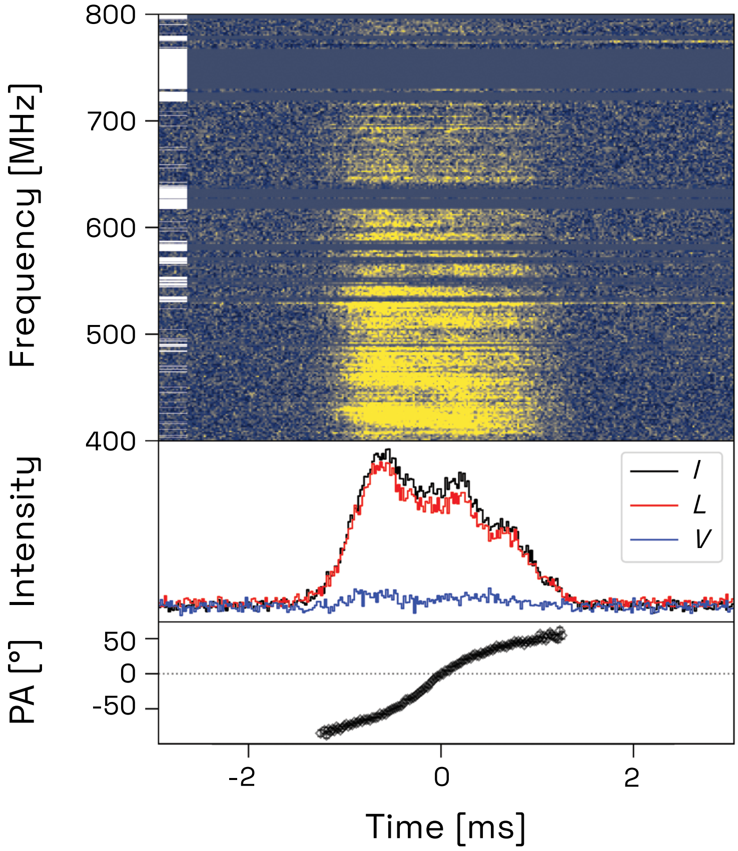

FIGURE 4:
FRB 20221022A. The top panel show the dynamic spectrum of the FRB: its intensity as a function of time and frequency. The middle panel shows its frequency-averaged pulse profile in intensity (I), and linear (L) and circular (V) polarizations. The bottom panel shows the angle of the linear polarization. The characteristic S-shaped swing of the polarization angle is a hallmark of emission from a rotating magnetic field. (Adapted from Mckinven, R., Bhardwaj, M., Eftekhari, T. *et al.* "A pulsar-like polarization angle swing from a nearby fast radio burst." *Nature* **637**, 43–47, 2025).

Zooming in on the emission

In the early days of FRB research—when the total number of known bursts could be counted on your fingers and a few toes—I observed, for the first time, scintillation in an FRB caused by gas in the Milky Way. This allowed me to effectively "zoom in" on the environment of the source, showing it lived in a dense environment typical of magnetars. That observation offered circumstantial support for the magnetar progenitor hypothesis—some of the strongest such evidence available at the time. But even that accomplishment was a long way from answering the deeper question of how FRBs are produced. It gave hints about the surroundings of the source, but not the nature of the emission mechanism itself.

Our latest discovery takes the scintillation method a significant step further. We set out to search CHIME's archive for FRBs that had experienced scintillation twice—that is, FRBs showing two distinct frequency scales in their interference pattern. We reasoned that this could only happen if the burst had been lensed by gas both in the Milky Way and in its own host galaxy. And crucially, the lens in the host galaxy—being much closer to the FRB source—would provide much finer resolving power, allowing us to zoom in much more tightly on the emission region.

Eventually, we found what we were looking for in FRB 20221022A—named, like all FRBs, for the date it was detected. This burst was ideal in several respects: its host galaxy is relatively nearby, at just 200 million light-years, and the FRB itself was bright, providing ample signal-to-noise for detailed spectral analysis. When we examined the burst's spectrum, we found two distinct scintillation frequency scales, at 120 kHz and 6 kHz. By analyzing this double-lensed interference pattern, using both the geometric information contained in these frequency scales and the coherence of the interference in each lens, we inferred that the size of the emission region was no more than 30,000 kilometers.

It's the magnetosphere–this time

Our measurement—that the FRB emission region is no larger than 30,000 kilometers—places a strong constraint on the viable emission mechanisms. This size limit is inconsistent with shock-based models, which predict that the radio waves are generated far from the neutron star, more than hundreds of thousands of kilometers away. By contrast, the observation is entirely compatible with magnetospheric models, where the emission originates much closer to the neutron star, within the region dominated by its magnetic field.

This FRB also carried a second clue pointing in the same direction. Over the few-millisecond duration of the burst, the polarization angle of the radio waves exhibited a smooth and characteristic swing. Such polarization swings are well known from pulsars, where they arise from the rotation of the neutron star. As the star spins, the orientation of its magnetic field vector changes with respect to our line of sight, producing a systematic sweep in the polarization angle. Seeing a similar signature here adds further support to the idea that the emission is tied to the rotating magnetosphere of a neutron star.

While these observations may seem to close the book on shock models for FRB emission, the picture is not so simple. This is, after all, just one FRB—a single event among the thousands that CHIME has observed. And so far, we haven't been especially systematic about looking for similar signatures in the rest of the population.

Our ability to make these measurements depended on several fortunate alignments: gas lenses needed to be present both in the Milky Way and in the host galaxy, positioned just right to produce distinct scintillation patterns. The FRB also had to be bright enough to allow for detailed spectral and polarization analysis. It's unclear how often this precise combination occurs, which introduces a degree of selection bias if we try to generalize these results too broadly.

Still, as with the discovery linking at least one FRB to a magnetar progenitor, this finding gives us an important existence proof: some fraction of FRBs originates from magnetospheric emission. That alone marks significant progress—and provides a concrete foundation on which to build a more complete understanding of these mysterious cosmic flashes. Each clue adds to a growing picture: fast radio bursts are no longer just mysterious flashes in the dark. They're becoming a story we can tell.

REFERENCE

[1] Nimmo, K., Pleunis, Z., Beniamini, P. et al. "Magnetospheric origin of a fast radio burst constrained using scintillation." *Nature* **637**, 48–51 (2025).

PROFESSOR KIYOSHI MASUI's Synoptic Radio Lab works with wide-field, radio-wavelength sky surveys to establish new ways to observe the Universe. These include developing the technique of hydrogen intensity mapping for rapidly surveying large volumes of space, and exploiting the recently-discovered phenomena of fast radio bursts (FRBs) as probes of the Universe's contents. This work includes creating digital instrumentation for radio telescopes, developing algorithms for analyzing observational data, and making theoretical predictions for the signals we should be looking for.

Kiyoshi Masui studied engineering physics at Queen's University in Canada and did his undergraduate thesis in experimental astroparticle physics. He received his PhD in physics in 2013 in the Canadian Institute for Theoretical Astrophysics (CITA) at the University of Toronto. For his graduate work he led one of the first radio surveys to use hydrogen to map large-scale structure beyond the local universe. He then moved to the University of British Columbia as a Canadian Institute for Advanced Research Global Scholar and subsequently a CITA National Fellow. Masui joined the MIT Department of Physics as an assistant professor in 2018.