Plenty of Room at the Bottom

Fast Radio Bursts in our Backyard
Cornell University, October 2022

Plenty of Room at the Bottom: Fast Radio Bursts in our Backyard
Cornell University, 10-11 October 2022

The lowest luminosity and the nearest FRBs have, thus far, provided a clear connection between FRBs and magnetars. The same phenomenon may help us understand the gap between giant radio pulses and FRBs, or perhaps bridge the two phenomena, possibly along with others. So, we thought a workshop focused on such FRBs was timely. October in Ithaca is colorful and "gorge-ous".

Thanks to advances in technology, talks which are primarily informational can be prepared ahead of the meeting and reviewed by the attendees. However, live discussion is best done in person and that is what we, the organizers, wished to preserve. We planned to devote half of the time for discussions and the remaining time for talks. Since the meeting was short, a mere two days, not all participants could give live talks. These two requirements led to us a style of meeting distinctly different from the usual approach. What follows is the instructions to the participants.

Instructions to participants: The meeting consists of six 2-hour sessions, of which one hour will be used for three 15+5-minute talks and the remaining hour for moderated discussions (see below for summary of sessions). To this end, we are requesting that participants submit a 20-minute video recording of their talk along with pdf file of the slides. In addition, we request a <1.5-page summary of each talk and <0.5-page self-introduction from each participant by September 12th. Feel free to include figures in the summary. Please ensure that your contribution does not exceed two pages. Some of you may not be interested in giving a talk. In such cases, please provide <0.5 page of self-introduction. We will be collating these submissions and provide them as a pdf file ahead of the meeting, as well as a hard copy (with additional blank pages for notes).

Please note that the deadline is the Fall equinox (September 22nd). The organizers and the chairs of the sessions will, following a review of these talks, construct the final agenda for the meeting. More importantly, we hope that all participants will review the talks and thus come well-prepared to the meeting. Equally, we hope that all participants will use this facility and provide a talk.

The meeting schedule: The meeting consisted of six 2-hour sessions with each session consisting of three 20-minute talk and the remaining time devoted for discussion:

1. *Are there multiple FRB populations?*
2. *What do modelers want from observers, and vice versa?*
3. *The local environment of FRBs (on pc to kpc scales).*
4. *Connecting FRBs with the cosmic web (d<1 Gpc).*
5. *FRBs in the Milky Way and the Local Group.*
6. *Near-term plans and flash news.*

Each session had two chairs who selected the submitted talks and were also responsible for managing the discussions. The list of participants, the schedule of the live talks and the collection of abstracts & biographies follow this introduction. The collection of pre-meeting recorded talks can be found at http://hosting.astro.cornell.edu/research/frb/FRB-Workshop-2022/

S. Chatterjee, J. Cordes & S. R. Kulkarni, Cornell University, Ithaca, NY 14-October-2022

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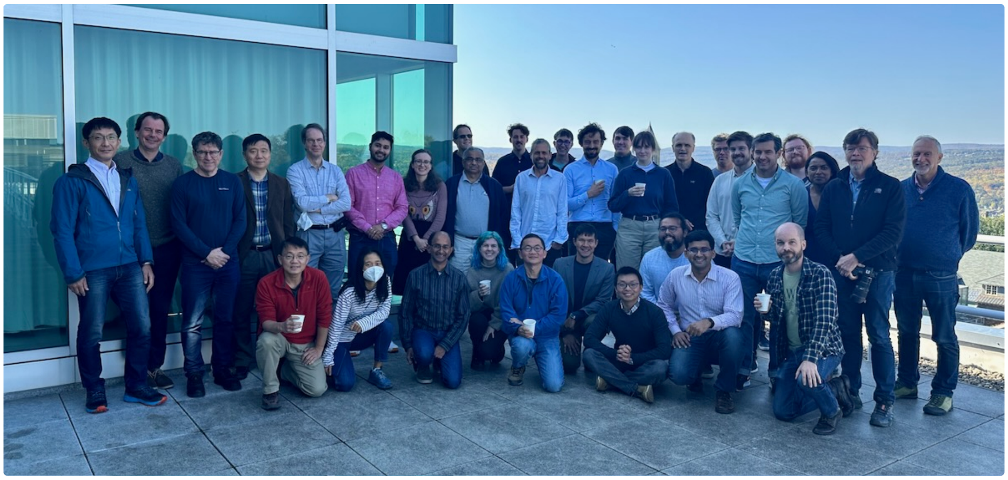
Meeting Participants



Matthew Bailes, Swinburne -- [Bio]

Keith Bannister, CSIRO -- [Abstract]

Nick Bataglia, Cornell -- [Bio]

Andrei Beloborodov, Columbia -- [Abstract]

Mohit Bhardwaj, McGill -- [Abstract]

Manisha Caleb, Sydney -- [Abstract]

Shami Chatterjee, Cornell -- [Bio]

Liam Connor, Caltech -- [Abstract]

Amanda Cook, Toronto -- [Abstract]

Jim Cordes, Cornell -- [Abstract]

Emmanuel Fonseca, WVU -- [Abstract]

Jason Hessels, Amsterdam -- [Abstract]

Anna Ho, Cornell

Kunihito Ioka, Kyoto -- [Abstract]

Marten van Kerkwijk, Toronto -- [Abstract]

Shri Kulkarni, Cornell -- [Abstract]

Pawan Kumar, Austin -- [Abstract]

Dong Lai, Cornell -- [Bio]

Casey Law, Caltech -- [Abstract]

Joeri van Leeuwen, ASTRON -- [Abstract]

Dongzi Li, Caltech -- [Abstract]

Wenbin Lu, Berkeley -- [Bio]

Maxim Lyutikov, Purdue -- [Abstract]

Kiyoshi Masui, MIT -- [Abstract]

Brian Metzger, Columbia -- [Abstract]

Sasha Niedbalski, Cornell -- [Abstract]

Kenzie Nimmo, Amsterdam -- [Abstract]

Stella Ocker, Cornell -- [Abstract]

Ue-Li Pen, ASIAA -- [Abstract]

Sterl Phinney, Caltech -- [Bio]

Ziggy Pleunis, McGill -- [Abstract]

Kiran Shila, Caltech -- [Abstract]

Shriharsh Tendulkar, TIFR -- [Abstract]

Christopher Thompson, CITA -- [Abstract]

Ira Wasserman, Cornell

Dan Werthimer, Berkeley -- [Abstract]

Bing Zhang, Nevada -- [Abstract]

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Meeting Schedule

Day 0	**Sunday 9th October**
9 AM	Group excursion to the Corning Museum of Glass (bus from Ithaca) Chartered bus ("Swarthout") will pick up at the Hotel Ithaca — [Google Maps]; [Apple Maps]
2:30 PM?	Return to Ithaca
3 PM	Group excursion to the Sheldrake Point winery on Cayuga lake (bus from Ithaca) Chartered bus ("Swarthout") will pick up at the Hotel Ithaca — [Google Maps]; [Apple Maps]
6 PM?	Return to Ithaca

Day 1	**Monday 10th October**

Meeting in 401 Physical Sciences Building — [Google Maps]; [Apple Maps]

8:30 AM	Refreshments and Coffee (provided)
8:45 AM	Welcome from the Dean and the Department Chair
9:00 AM	Session 1. Are there multiple FRB populations? Chairs: Zhang, Hessels Live talks: Caleb, Nimmo, Pleunis; Panel discussion.
11:00 AM	Coffee Break
11:15 AM	Session 2. What do modelers want to see from observers, and vice versa? Chairs: Metzger, Pleunis Live talks (short): Lyutikov, Thompson, Zhang, Ioka, van Kerkwijk; Discussion.
1:30 PM	Lunch Break - multiple options on and off-campus
3:00 PM	Session 3. The local environments of FRBs Chairs: Tendulkar, Thompson Live talks: Law, Li, Metzger; Discussion.
5:00 PM	Sessions end
6:00 PM	Dinner - Baker portico, Physical Sciences Building (catered)

Day 2 Tuesday 11th October

Meeting in 401 Physical Sciences Building — [Google Maps]; [Apple Maps]

8:30 AM	Refreshments and Coffee (provided)
9:00 AM	Session 4. Connecting FRBs with the local cosmic web Chairs: Phinney, Battaglia Live talks: Ocker, Masui, van Leeuwen; Discussion.
11:00 AM	Coffee Break
11:15 AM	Session 5. FRBs in the Milky Way and Local Group Chairs: Lu, Connor Live talks: Cook, Connor, Kulkarni; Discussion.
1:30 PM	Lunch Break - multiple options on and off-campus
3:00 PM	Session 6. Near-term plans, projects, and newsflashes Chair: Chatterjee Live talks: Bannister, Tendulkar, Pen, Werthimer; Discussion.
5:00 PM	Sessions end
Evening	Dinner - at Coltivare, downtown Ithaca (catered) [Google Maps]; [Apple Maps]

Shami Chatterjee, 7 October 2022 Design adapted from HTML5 UP.

Keith Bannister – About me

Hello! My name is Keith Bannister. I'm part astronomer, part instrumentalist, with emphasis on the mental. I work at the Australia Telescope National Facility (ATNF) which is like the National Radio Astronomy Observatory (NRAO) but in Australia. We operate some radio telescopes you may have heard of, like the Murriyang 64m at Parkes, which was the first telescope to detect a Fast Radio Burst (FRB); and the Australian Square Kilometer Array Pathfinder (ASKAP), which was the first telescope to localize a once-off FRB.

I first heard of FRBs in my first group meeting as a PhD student. I was walking into Bryan Gaensler's office with Shami, and they were excitedly talking about this paper reporting something weird, and it had lots of Janskys. I didn't know what a Jansky was, but it sounded impressive to me! That sort of mystery was exactly what I find exciting in science.

I'm most interested in using FRBs as tools to find out things about the Universe that are difficult to find out any other way. It would be great to know what makes FRBs too, but once you know what they are, I feel like you've answered the question, and the party grinds to a halt. But if you can use them as tools, who knows what whacky thing you could measure if the right FRB?

I work with the CRAFT collaboration which primarily uses ASKAP. My favorite results so far have been the measurement of the "Macquart" relation and the measurement of the Hubble constant. Jean-Pierre Macquart was a good friend and enthusiastic collaborator in CRAFT. He died right after publishing his relation now named after him.

Outside of astronomy, I have officially too many kids (Arianne – 14, Soren 13, Huon 10). I like taking them on adventures skiing, sailing, hiking, rock climbing, surfing. I'm building a foiling electric kayak with some friends. I play trombone badly.

The value of large-area surveys

To date, most FRBs with known redshifts have been found in the redshift range $0.1 < z < 1$. We would like to find, and localize FRBs in the nearby universe because:

- It's easier to study their immediate environments
- We have a better chance of identifying prompt, and afterglow emission (if any) at other wavelengths
- We can begin to make a map of the intergalactic medium in the Galactic neighborhood, which might be useful if we get lost.

Large-area surveys also have the advantage that they can find the rarest types of FRBs, e.g. most energetic ones. Setting a constraint on the maximum energy that can be emitted by an FRB helps us understand the emission mechanism.

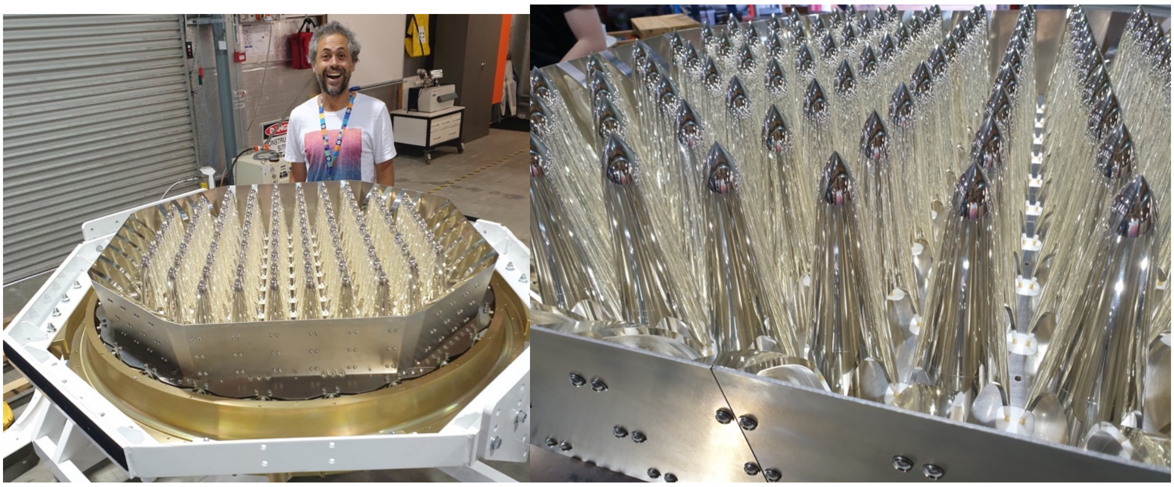
Large area surveys require instruments with large fields of view. This is where phased array feeds (PAFS) are useful.

Large area surveys using Phased Array Feeds (PAFs) as aperture arrays

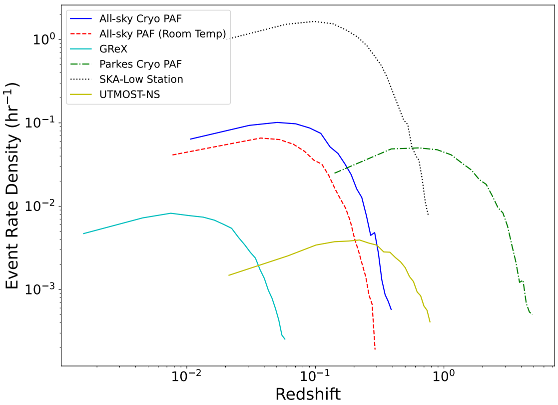
Phased array feeds use many closely-spaced antennas to make a large antenna. At ASKAP and Murriyang we normally install them at the prime focus of a dish, which makes the observations sensitive, but reduces the field of view. We're thinking of doing an FRB survey with some new PAFs we're building. Instead of installing them on a dish, we'll leave them on the ground and point them upwards.

The CryoPAF

This is the CryoPAF. It's designed by my friend Alex Dunning, who is a genius. Everything Alex makes is high-performance, covered in gold, and expensive. Unless it's high-performance, covered in silver and expensive. CryoPAF elements are called "rockets" and are covered in silver to improve their thermal radiation properties. That's me standing next to it. You can see I'm excited about it.



Rui Luo has done some modelling of how many FRBs the CryoPAF would find, both installed on the dish (as is planned), and on the ground pointing upwards (which we might try to wrangle if we can). The CryoPAF will find an FRB about every 10 days at a redshift less than 0.1. Multiple CryoPAFs like this could localize the FRBs too.



"Quasar" and future phased array feeds

We're building and thinking about more phased array feeds after the CryoPAF.

- The "Quasar" PAF will operate at around 3 GHz, it might be useful for finding magnetars in the galactic plane.
- Alex wants to try optimising the CryoPAF to make it work at room temperature. This PAF would have a much larger spacing, and hence collecting area, and only small increase in system temperature.
- This room temperature PAF would be a useful demonstrator for an upgraded ASKAP PAF.

Professor Matthew Bailes
Swinburne University of Technology

My name is Matthew Bailes and I have been interested in Fast Radio Bursts since early 2007, when Duncan Lorimer showed me two apparently simultaneous dispersed pulses in adjacent beams of the Parkes Multibeam receiver while we were observing together in the Parkes telescope. Over the next few days we retrieved the filterbank data of the bursts and displayed their waterfall plots, and saw the unmistakable dispersed pulse of the Lorimer Burst. It became apparent that one of the 13 beams of the receiver had triggered the radio frequency rejection algorithm, and when we retrieved the original data saw that the burst had saturated the receiver and been replaced by fake data! At first the Lorimer Burst seemed too good to be true, but history has shown that it was the first FRB and part of a cosmological population.

In 2009 I helped design the hardware system for the Parkes High Time Resolution Universe survey that eventually discovered the Thornton et al. (2013) bursts that established the cosmological population, and worked to implement GPUs in real-time FRB detection and to dump full Stokes parameter information.

My team built a new backend for the Molonglo radio telescope, and its wide field of view enabled us to detection more FRBs at low frequencies, including a voltage capture mode for the coherent dedispersion of FRBs. This helped detect microstructure in some of the FRBs with timescales down to 30 us. I helped Hyeron Cho develop a high time resolution dedispersion system for ASKAP that was used in the study of one of its first FRBs, revealing a 4-component FRB.

I have an interest in the origin and evolution of binary pulsars, that may be of relevance to FRBs.

Nick Battaglia

My research background is in observational cosmology, mostly focussed on topics related to secondary anisotropies in the cosmic microwave background (CMB, e.g., using the CMB as backlight). With these secondaries I have worked on: galaxy clusters both from a cosmological and astrophysical perspective; cross-correlations with large-scale structure including measuring the thermal and kinetic Sunyaev-Zeldovich effects; the epoch of reionization developing quick, large-scale reionization models and CMB observables; higher order statistics of secondary anisotropies and their cosmological and astrophysical information. The scope of my research spans theory to observations. This includes developing new models, simulations, and statistical estimators, analyses and interpretation of observations, and making new measurements from various cosmological surveys. In addition to cosmology and large-scale structure, lately I have been interested in circumgalactic medium (CGM) and new probes of the CGM.

For this meeting, my interests overlap with Fast Radio Bursts (FRB) through the use of them as backlights to illuminate the free electrons between us and the FRB sources.

Educational/Professional Background:
BSc McGill University 2006, Phd University of Toronto 2011 (Adviser: J. R. Bond), McWilliams Postdoctoral Fellow Carnegie Mellon University 2011 - 2014, Lyman Spitzer Fellow Princeton University 2014 - 2017, Associate Research Scientist Flatiron Institute Center for Computations Astrophysics 2017 - 2018 (Deferred Cornell University Position), Assistant Professor Cornell University 2018 - present.

Damping of GHz waves in magnetar magnetospheres

Andrei Beloborodov

Suppose a GHz burst is emitted near a magnetar. For example, consider a sine radio wave $E(\xi) = E_0 \sin(\omega\xi)$ where $\xi = t - r/c$ and r is the radial distance from the star. We wish to know how the radio wave evolves as it expands to larger radii r through the magnetosphere of the magnetar. This is a well posed physics problem, which can be solved. As long as the magnetospheric particles exposed to the wave remain magnetized (i.e. their Larmor frequency far exceeds the wave frequency ω) the radio wave obeys MHD and can be thought of as a fast magnetosonic wave in the strongly magnetized background. Below the solution to this problem is summarized (details are given in Beloborodov 2022, in preparation).

As the radio wave expands to larger r, it initially experiences no effects from the background magnetosphere — it propagates as in vacuum, with no change in the wave profile apart from the decrease of amplitude $E_0 \propto r^{-1}$. In particular, the wave power $L = cr^2 E_0^2/2$ remains unchanged. This behavior holds as long as E_0 remains small compared with the background magnetic field $B_{\rm bg} = \mu/r^3$, where μ is the magnetic dipole moment of the star. The behavior drastically changes when the wave approaches radius $R_\times$ where $E_0 = B_{\rm bg}/2$,

$$R_\times = \left(\frac{c\mu^2}{8L}\right)^{1/4} \approx 2.5 \times 10^8 \, \frac{\mu_{33}^{1/2}}{L_{42}^{1/4}} \text{ cm.} \tag{1}$$

Near this radius, each oscillation of the wave steepens into a shock. Then, the shock dissipation continues to damp the wave oscillations and practically erases them. One example is shown in Figure 1. It assumes a typical magnetar magnetosphere with $\mu = 10^{33}$ G cm^{-3} and $e^\pm$ plasma density $n(r) = 10^{13}\, r_8^{-3}$ cm^{-3}. Note that at radii of interest, $r \gtrsim R_\times$, the magnetosphere consists of mildly relativistic particles (before the arrival of the wave), as their motion is limited by drag exerted by radiation flowing from the magnetar (Beloborodov 2020, ApJ).

The damping effect is further demonstrated in Figure 2. It shows the wave power evolution with radius for two GHz bursts, with initial luminosities $L = 10^{42}$ erg/s and 10^{40} erg/s.

The wave evolution in these examples was calculated in the equatorial plane of the magnetosphere, $\theta = \pi/2$, where the background magnetic field $\mathbf{B}_{\rm bg}$ is perpendicular to the wave propagation direction. Similar shock damping will occur at latitudes $\theta \neq \pi/2$ where $\mathbf{B}_{\rm bg}$ is oblique to the radially expanding wave. The vacuum propagation fails where it predicts $B^2 - E^2 \leq 0$, which leads to shock formation and damping of wave oscillations. This condition is met on the surface

$$r(\theta) = \left(\frac{1 + 3\cos^2\theta}{\sin\theta}\right)^{1/2} R_\times. \tag{2}$$

There is a narrow cone near the magnetic axis $\theta < \theta_{\rm esc}$ where the radio burst could escape. A typical $\theta_{\rm esc} \sim 10^{-2}$ implies a small probability $\sim \theta_{\rm esc}^2/2$ for the line of sight to be within the escape cone.

The MHD calculation fails for radio bursts with $L < 10^{40}$ erg/s. Then a kinetic description is required. It also gives strong damping of the wave (Beloborodov 2022, PRL).

Our main conclusion is that observed FRBs can hardly be emitted by a source confined in the inner magnetosphere of a magnetar. FRBs must be emitted outside the magnetosphere by magnetospheric explosions. Possible mechanisms include ejecta modulated by reconnection (Lyubarsky 2020, ApJ) or blast waves in the magnetar wind (Beloborodov 2017, 2020, ApJ).

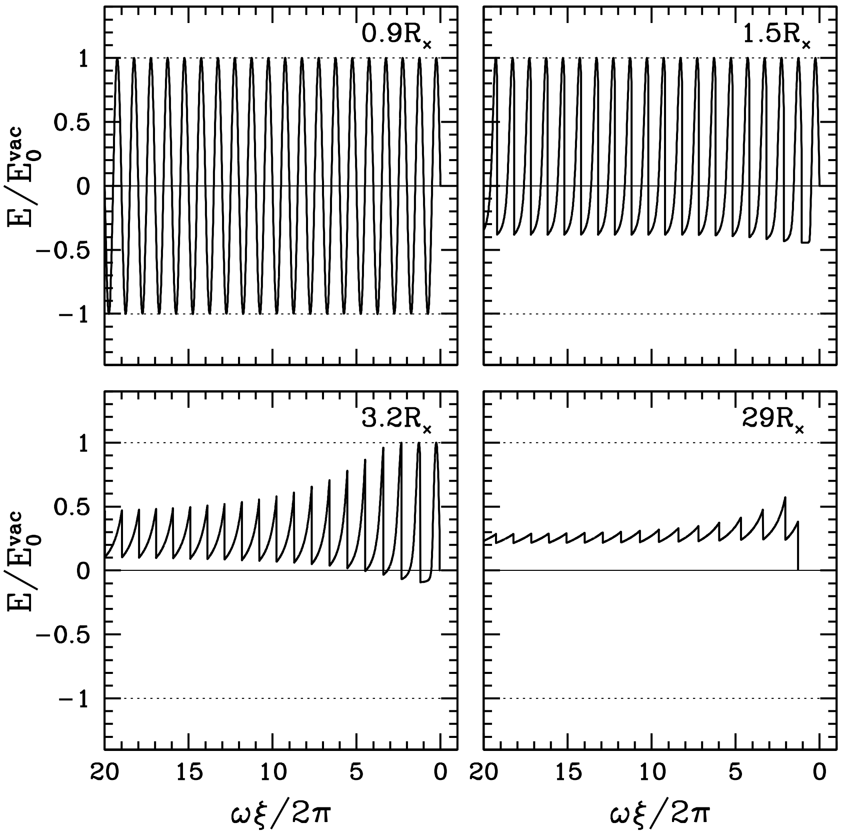


Figure 1: Evolution of the wave profile $E(\xi)$, where $\xi \equiv t - r/c$. In this example, the wave has frequency $\nu = 0.3\,\mathrm{GHz}$ and initial power $L = 10^{42}\,\mathrm{erg/s}$. The snapshots were taken when the wave reached $r/R_\times = 0.9$, 1.5, 2.6, and 29. For clarity only the leading 20 oscillations are shown (the simulated burst has 3×10^4 oscillations). At $r > R_\times$, each oscillation forms a strong shock. The wave electric field E in each panel is normalized to the amplitude $E_0^{\mathrm{vac}}(r)$ that the wave would have in vacuum.

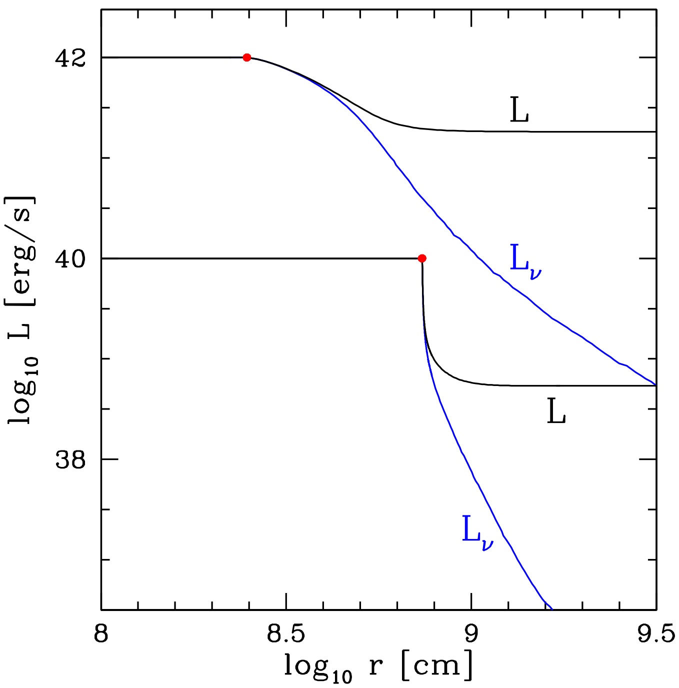


Figure 2: Evolution of wave power calculated for 0.3 GHz bursts with initial $L = 10^{42}\,\mathrm{erg/s}$ and $L = 10^{40}\,\mathrm{erg/s}$. The bursts have 0.1 ms duration. Power of the oscillating component L_ν is shown by the blue curve, and total Poynting flux L is shown by the black curve. The moment of shock formation (near $R_\times$) is indicated by the red dot. One can see that the wave oscillations are damped by more than 3 orders of magnitude. Most of the wave energy is converted to synchrotron X-rays, and part of it converts to a non-oscillating Poynting flux with the 0.1 ms duration.

(Beloborodov 2022, in preparation)

Deciphering the Origins of FRBs using Local Universe CHIME Bursts

Fast radio bursts (FRBs) are energetic radio pulses of high brightness temperature ($\sim 10^{35}$ K) and millisecond duration. In spite of the fact that more than 1000 FRBs have been discovered to date, their nature continues to be a subject of intense debate, owing in part to a limited sample of localized FRBs. To unveil the nature of FRB sources, identification of FRB multi-wavelength counterparts as well as detailed analyses of their hosts and local environments are promising approaches. However, due to the limited sensitivity of current telescopes, these approaches are best suited for local Universe FRBs.

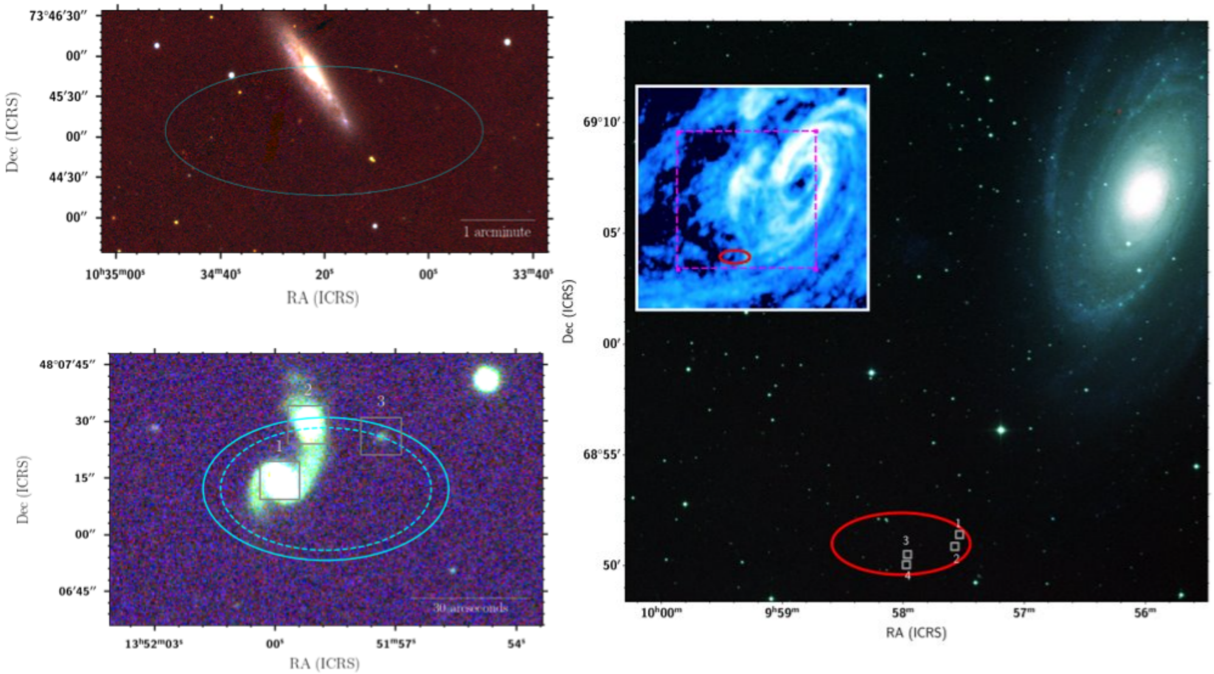


Figure 1: Low-DM CHIME FRBs: The figure shows a subset of localized low-DM CHIME FRBs: (top left) FRB 20181030A host (NGC 3252; 20 Mpc), (bottom left) FRB 20190303A host (Merging pair, [PA2008] 207.996573+48.12472; z = 0.064), and (right) FRB 20200120E host (M81; 3. Mpc). In each plot, a solid ellipse represents a 90% confidence localization region.

The Canadian Hydrogen Intensity Mapping Experiment (CHIME)/FRB project has been detecting FRBs since July 2018, and many of them have sufficiently low dispersion measures (DMs) suggesting a nearby origin. Even better, the localization of low-DM FRBs to a few arcminutes precision using the CHIME/FRB baseband system can result in a reliable host association for nearby FRBs. These local Universe FRBs have made a significant contribution to our understanding of FRB origins. FRB 20200120E, for example, which was discovered as part of the low-DM CHIME/FRB project, is located in a globular cluster of M81, which is a conglomeration of very old star populations. It is one of the last places we expected to find FRBs because the most prevalent FRB model invokes young highly magnetized compact objects (like Galactic magnetar SGR 1935+21) produced via prompt formation channels like core-collapse supernovae, long gamma-ray bursts, and superluminous supernovae. This discovery provides the strongest evidence yet for the existence of multiple FRB formation channels. Moreover, multi-wavelength follow-ups of these local Universe CHIME FRBs have enabled stringent limits to be placed on high-energy counterparts than for more distant FRBs, which are the majority of the FRBs localized to a host galaxy to date.

In my talk, I will report on the CHIME/FRB discoveries of several local Universe FRBs (three are shown in Figure 1) and the constraints we derived on different proposed FRB source and emission models. These local Universe FRBs are found to bridge the gap between Galactic (radio-loud) neutron stars and the much more distant extragalactic FRBs in the radio transient (∼GHz) phase-space. I will also discuss the constraints we derived on the distribution of hot ionized baryons in the circumgalactic medium of the Milky Way using the localized nearby CHIME bursts, and how we can combine them with halo gas probes in the UV and X-ray bands. Finally, I will discuss the application of Local Volume galaxies in order to understand the nature of the FRB luminosity function.

About the Author

Mohit Bhardwaj is currently a McWilliams postdoctoral fellow at Carnegie Mellon University, USA. He received his bachelor's degree in electronics and electrical engineering and has an integrated master's degree in Physics from BITS Pilani (India). He will soon receive his PhD in Physics from McGill University. His research interests include astrophysical transients, interstellar medium, astrostatistics, observational cosmology and radio instrumentation. Mohit is a member of the CHIME/FRB project. Within the CHIME/FRB collaboration, he is leading the multi-wavelength follow-up and host association of local Universe FRBs. In his PhD work, he used local Universe CHIME bursts to decipher the origins of FRBs. FRBs, he believes, can provide a unique view into the aftermath of some of the Universe's most violent events. In addition to solving the FRB origin problem, he wants to use FRBs to map the cosmic web. Finally, he is always on the lookout for unexplored enigmas of the Universe. So, if you know of any, don't hesitate to contact him.

Connecting the dots: From ultra-long period neutron stars to fast radio bursts

Since the discovery of neutron stars over five decades over, more than 3000 of these enigmatic objects have been discovered. Neutron stars come in a variety of flavours ranging from millisecond pulsars to the more recently discovered Ultra-Long Period Neutron Stars (ULPNSs). The discovery of the latter, emitting unusual radio signals is rewriting our understanding of these unique star systems. Recently, a couple of such long period neutron stars have been found to reside in the neutron star graveyard and yet produce radio emission. The most recent ULPNS, PSR J0901-4046 discovered with the MeerKAT telescope in South Africa lives in the neutron star graveyard and completes one rotation every 76 seconds. It exhibits highly unusual, and chaotic pulse shapes quite unlike anything seen in known neutron stars, with certain features reminiscent of magnetars. In some of the bright pulses we measure a quasi-periodicity in the sub-pulse components (Figure 1: panels f and g) which at times appear to be harmonically related between pulses. In some others we see multiple quasi-periods within a single rotation. Similar quasi-periodic features have been observed in a sample of fast radio bursts (FRBs) (Figure 1: panels a, b and c). Interestingly, radio observations of the magnetar XTE J1810−197 following its 2018 outburst revealed a persistent 50-ms periodicity imprinted on the pulse profile.

While PSR J0901-4046 exhibits a range of quasi-periods between single pulses, the most commonly observed quasi-period follows the spin-period scaling seen in corresponding values of the micro-pulses in normal pulsars. However, the appearance of the dropouts (Figure 1: panels f and g) is different to that of normal micro-pulses. In contrast, it is very reminiscent of quasi-periodic oscillation (QPO) features seen both in the emission of hard short X-ray bursts and the tail of energetic giant flares of magnetars and is very unusual for pulsar radio emission. Such quasi-periodic oscillations are also theorized in models of FRBs, where they are due to magneto-elastic axial (torsional) crustal eigenmodes originating close to the neutron star surface. Ultimately, it is unclear what causes the quasi-periodicity in PSR J0901−4046. Global magnetoelastic axial (torsional) oscillations are a tempting explanation, but the persistence of our periodicities would require repeated triggers and/or very long damping times. The observed periodicities and frequencies, however, may be consistent with models proposed for magnetars, and the similarity with the periodic feature of the radio-loud magnetar XTE J1810−197 are intriguing. PSR J0901−4046 is therefore an important piece in the puzzle of the evolution of highly magnetized neutron stars and their connection to FRBs. Continued monitoring of the object will tell us whether it can produce pulses with FRB-like energies similar to what was seen from the Galactic magnetar SGR 1935+2154.

Biography:

Manisha Caleb is presently a Discovery Early Career Researcher Award fellow, and lecturer based at the University of Sydney in Australia specialising in radio transients, particularly fast radio bursts (FRBs). She is involved with collaborations at the MeerKAT and ASKAP radio telescopes to discover, study and understand the enigmatic FRB phenomenon. She is keen on observational studies of FRBs and takes particular interest in their polarisation properties. She continues to lead the international multi-wavelength collaboration to follow-up FRBs discovered with MeerKAT and study their host galaxies. She is currently interested in FRB cosmology and investigating a possible connection between FRBs and the more recently discovered ultra-long period neutron stars.

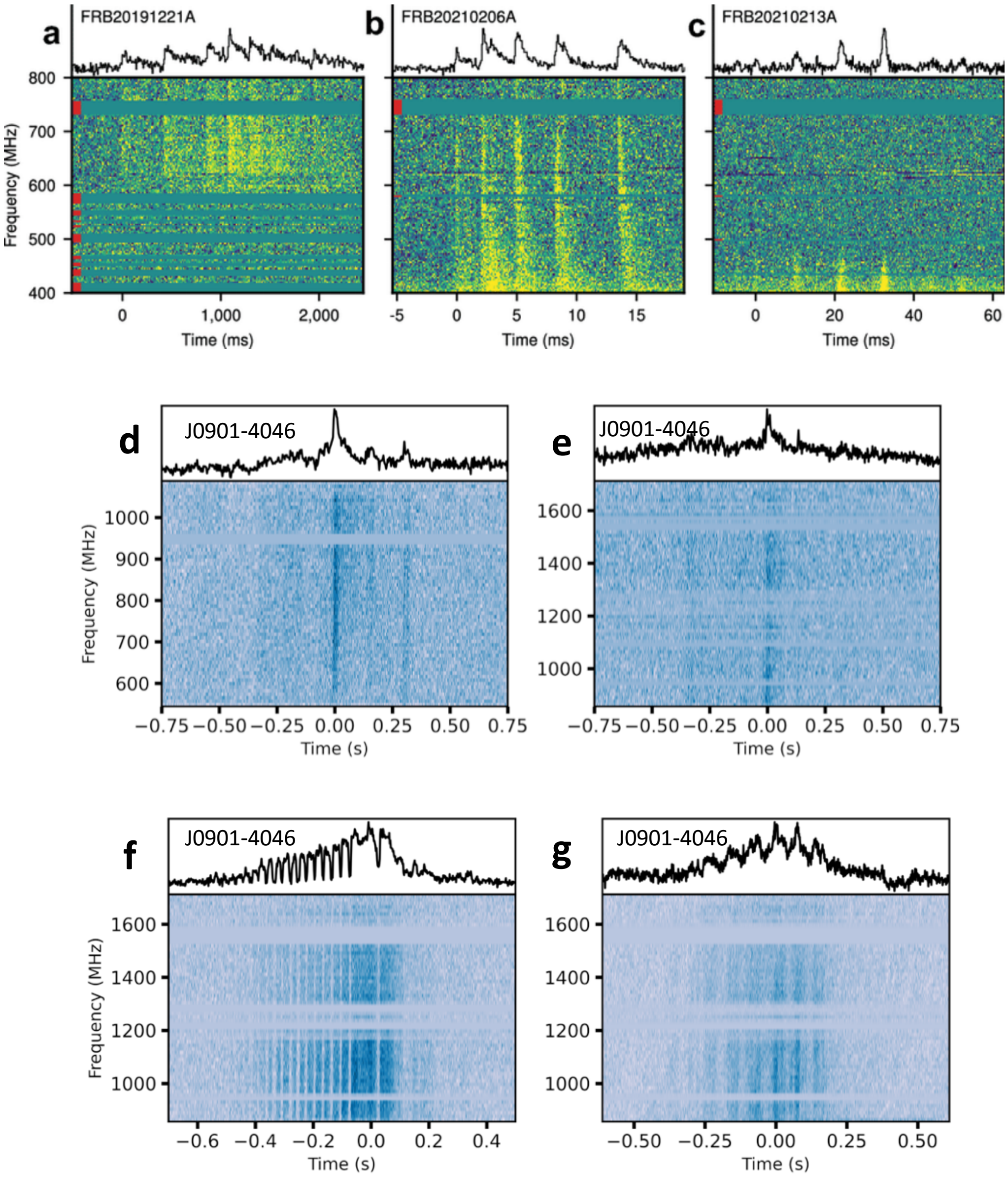


Figure 1: Example quasi-periodic pulses from FRBs (CHIME collaboration. 2022) and PSR J0901-4046

Shami Chatterjee
Principal Research Scientist and Research Professor, Cornell University

I am a Principal Research Scientist and a freshly-minted Research Professor at the Cornell University Department of Astronomy. I got my PhD at Cornell in 2003, focusing on astrometry and high-velocity pulsars, and then was a Jansky Fellow at NRAO in Socorro, NM and at the Harvard-Smithsonian Center for Astrophysics in Cambridge, MA. I then spent three years in Australia as a University Fellow at the University of Sydney and (briefly) a research scientist and a QEII Fellow at the Australia Telescope National Facility, before returning to Ithaca.

I got into Fast Radio Bursts for real when Laura Spitler, then a graduate student at Cornell, showed me a faint, barely-there single pulse she'd just found in Arecibo Pulsar-ALFA survey observations of the Galactic anticenter, and asked me if I thought it was real and worth following up. FRB 121102 certainly rewarded our persistence!

Along with FRBs, I work on building and characterizing the NANOGrav Pulsar Timing Array to detect low-frequency gravitational waves. I also dabble in high-frequency pulsar searches of the Galactic center with the Event Horizon Telescope, and run the Survey Science Group for the VLA Sky Survey. I'm involved with CHIME – especially the Outriggers project, which brings together VLBI, astrometry, pulsars, and FRBs – as well as DSA-2000, and other projects to explore the dynamic radio sky.

Liam Connor

1 Allow myself to introduce...myself

I am a Richard C. Tolman postdoctoral fellow at Caltech, beginning my third and final year in October. I did undergrad at McGill, grad at CITA/UofT, and a postdoc at ASTRON/Amsterdam.

My early Ph.D. work focused on 21 cm cosmology and commissioning the CHIME Pathfinder instrument. This was just before the Thornton paper was published and before anybody had proposed using CHIME to find FRBs. But by 2015, I was spending most of my time on FRB progenitor models, FRB statistics, and building a precursor time-domain pipeline on CHIME Pathfinder. I used the pipeline for an incoherent experiment to test the claim that the brightness distribution was significantly more flat than Euclidean, finding that it probably wasn't. This was all done in close collaboration with my PhD advisor at CITA, Ue-Li Pen. In 2016 and 2017, I spent some time in what I call "logN-logS Purgatory", where a number of us were attempting to extract knowledge from a small set of FRB population data, to little avail.

In the mean time, I have helped build/run Apertif and DSA-110, and I am currently working on the FRB and pulsar survey design for DSA-2000. My pipeline work has included building machine learning classifiers, beamformers, single-pulse injections and completeness, and analyzing the trade-space of FRB search parameters.

I am less interested in FRB emission physics, progenitor models, and population statistics than I once was. I am now more excited by FRB applications (baryon cosmology and, to a slightly lesser extent, gravitational lensing) and survey design (GReX & DSA-2000). Here are a few of statements about FRBs that illustrate my biases:

- Localization is paramount, 0.5–3 arcseconds is often good enough.
- Large numbers of unlocalized FRBs are not inherently valuable; their usefulness is largely in offering a better chance to find outliers (R3, M81, 190520, etc.).
- The baryon cosmology stuff is inevitable and also super cool.
- Coherent gravitational lensing is very exciting but will be hard to detect and *very* difficult to apply to H_0.
- The utility of efficient algorithms and clever survey design is tough to overstate.

2 GReX and future ChASMs

My talk will be on radio all-sky monitors and the search for FRBs in the Milky Way and local Universe. I will first describe our progress on the Galactic Radio eXplorer (GReX) and then offer a path forward for coherent all-sky monitors, or "ChASMs". For the foreseeable future, there will be a significant sensitivity gap between ultra-widefield surveys and traditional telescopes such as CHIME, DSA, and ASKAP. I will argue that GReX and ChASMs will fill an important niche in nearby FRB science.

When I heard Chris Bochenek give his talk on STARE2 at FRB 2018 in Melbourne, I was pleased that he and Shri were doing this experiment. And I was glad it wasn't me doing it. I thought that they would not find anything, but that the upper limits would be useful for constraining the FRB luminosity function. Fortunately, I was wrong. This was partly due to a too-clever-by-half argument about FRB repetition statistics (see Section 4.1 of Connor & Petroff (2018)) and partly because I didn't think the luminosity function would just carry on rising down to such small L. Turns out there was plenty of room at the bottom.

The co-detection of an FRB from SGR 1935+2154 by CHIME/FRB and STARE2 was the most significant FRB discovery to date. It unified an unexplained phenomenon (extragalactic radio pulses) with a known source class (magnetars) and opened up a window to studying FRB-like emission from within the Milky Way–including multiwavelength emission that is hard to detect for extragalactic events. Maybe the discovery was lucky, but consider that STARE2 could only see about 10 % of the sky at any given time, and due to its latitude ($\sim$+40 deg) STARE2 had limited exposure to the Galactic plane where most magnetars reside. It also had a system temperature of 65 K and limited radio bandwidth. Galactic FRBs must not be all that rare.

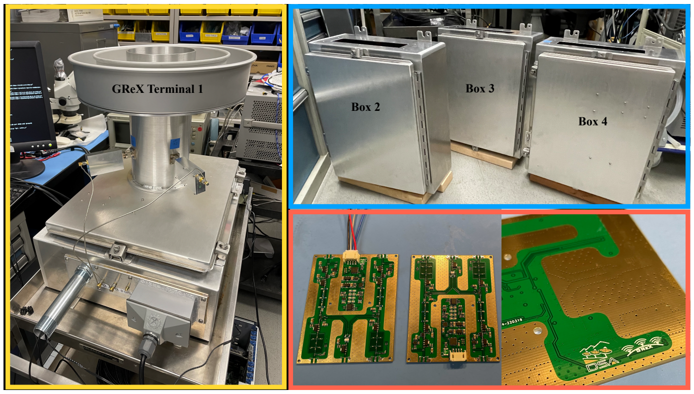


Figure 1: The first GReX terminal (yellow box). The next three GReX boxes, which house a front-end module, SNAPs, and timing (blue box). These will likely go to Australia. The custom front-end module, which performs the analog signal processing before the ADCs (red box).

For these reasons, it would be foolish to not expand our efforts to search for Galactic FRBs. We have proposed GReX as the first true radio all-sky monitor. Our plan is to deploy clusters of antennas around the world to build up to $4\,\pi$ steradians of continuous sky coverage. Each terminal will have roughly twice the sensitivity of STARE2 and will search down to 10 microsecond time resolution. With the increased sky coverage and improved sensitivity, we expect $\mathcal{O}(10)$ Galactic FRBs per year.

We are currently building the first 9 GReX terminals, amounting to three clusters that can be sent to different locations around the world. Our first non-US cluster will be sent to Australia in order to build up sensitivity to the Galactic plane. We will then deploy stations at Pierre Auger Observatory in Argentina, New York state near Ithaca, as well as Ireland and India eventually. The first terminal is now complete and is shown in Figure 1.

Despite the improvements in T_{sys} over STARE2, GReX is still an insensitive instrument. It will be able to find Galactic FRBs and, thanks to its high time resolution, supergiant pulses from pulsars. It will likely *not* find anything outside of our galaxy. The natural next step in ultra-widefield FRB surveys is a coherent all-sky monitor (ChASM), which would combine the signals from a large number of tightly-packed antennas and FFT beamform to fill the full 10^4 deg^2 FoV. Thanks to cheap beamforming and cheap GPUs, such a system would not be dominated by N^2 correlation costs. Instead, the costs would come from digitizing, channelizing, and searching a large number of antennas. In my talk I will go into greater detail on a ChASM successor to GReX, and I will discuss other efforts in this domain.

Self Introduction: My name is Amanda Cook, and I am a fourth-year Astrophysics PhD candidate at the University of Toronto and a member of CHIME/FRB. My supervisors are Prof. Bryan Gaensler, Prof. Gwen Eadie, and Dr. Paul Scholz. I come from a magnetar and pulsar background and I consider the ultimate goal of my career to answer the question '*Are all FRBs magnetars?*' My PhD thesis aims to use statistics to learn about the nature of FRBs as well as the foreground media that they illuminate. The first part of my thesis focuses on using extragalactic FRBs as probes of the ionized media in the Milky Way's halo, which is too diffuse to image directly using X-ray telescopes. Pulsar dispersion measures (DMs) have long been used to constrain the ionized plasma in the Galactic disk, however one does not expect the detectable pulsar population to extend far into the halo. FRBs, however, travel through the entire MW halo and hence we can use the lowest-DM FRBs to provide upper limits on the Galactic halo contribution to the DM. This allows us to place limits on the total mass and extent of the halo. A key question in understanding repeating FRBs is to determine just what fraction of FRBs repeat, and how frequently these repetitions occur. This is a difficult problem, because large numbers of FRBs are needed to obtain sufficient statistics, but large numbers of FRBs mean that there is a significant probability of seeing two bursts from the same position and DM, but which are from unrelated FRBs. My second thesis project is to establish a method, starting from first principles, to calculate the probability that an observed cluster of FRBs is physically related. These probability calculations play a vital role in defining the sample for CHIME/FRBs repeater catalogues, but are applicable in multiple disciplines like epidemiology. Finally, I coordinate and analyze high energy observations of repeating FRBs, in hopes to detect a prompt transient counterpart to a radio burst. Using CHIME/FRB as an activity monitor, we target nearby ($< 100\,\mathrm{Mpc}$), active, sub-arcsecond localized repeating FRBs for contemporaneous observations with X-ray telescopes and pointed radio telescopes like Effelsberg and GBT. We've secured one *XMM-Newton* ToO trigger for these purposes, and await a promising source.

Abstract: The CHIME/FRB project has detected hundreds of fast radio bursts (FRBs) providing an unparalleled population to statistically probe the foreground media that they illuminate. One such foreground medium is the ionized halo of the Milky Way (MW) which connects the intergalactic medium to the Galactic disk. We estimate the Galactic DM boundary from FRBs as a function of Galactic latitude using four different estimators, including ones that assume spherical symmetry of the ionized MW halo and ones that imply more variation in density. Our upper limits for the DM contribution of the halo, depending on the Galactic latitude and selected model, range between 52 and $111\,\mathrm{pc\,cm^{-3}}$. This implies observation-based high-latitude constraints on the total Galactic DM contribution which range over $87.8-141\,\mathrm{pc\,cm^{-3}}$.

If we impose additional priors, we can derive a maen MW halo DM estimate of $33^{+25}_{-22}\mathrm{pc\,cm^{-3}}$ from a joint Bayesian analysis. However, this relies on assumptions about the halo DM distribution and the DMs of FRB host galaxies. We discuss the viability of various gas density profiles for the MW halo that have been used to estimate the halo's contribution to DMs of extragalactic sources. Several models overestimate the DM contribution, especially when assuming higher halo gas masses ($3.5 \times 10^{12} M_{\odot}$). Some models are inconsistent with our observations unless the effect of feedback is increased within them, highlighting the impact of feedback processes in galaxy formation.

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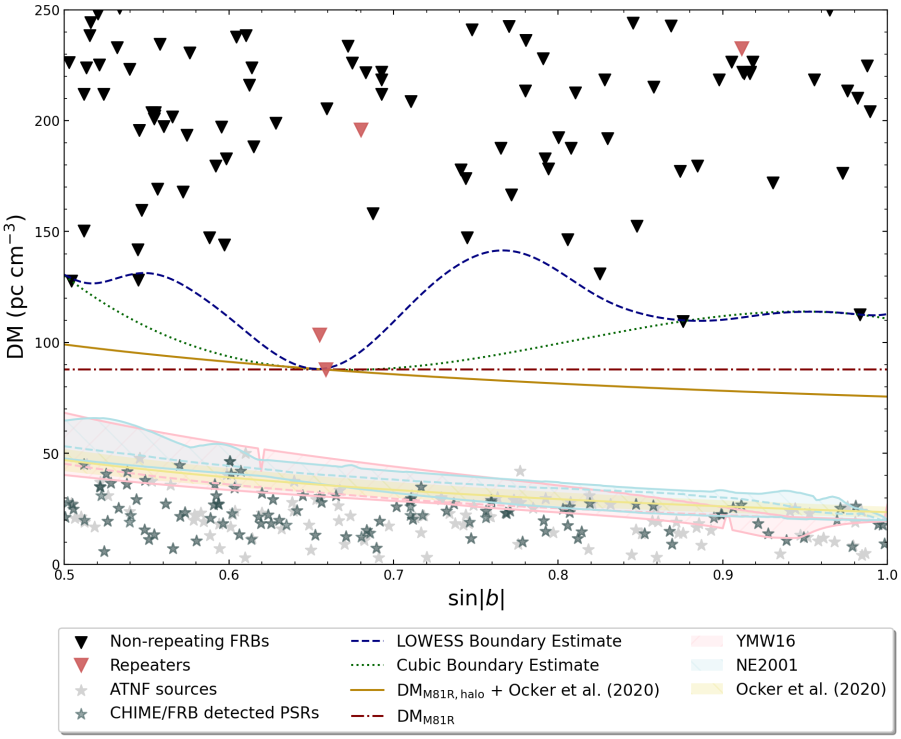

Figure 1: Total measured DM as a function of $\sin|b|$ for $|b| \geq 30°$ for FRBs detected by CHIME/FRB with DM less than $250\,\mathrm{pc\,cm^{-3}}$ through February 2021. Non-repeating FRBs are represented with black triangles and repeating FRB sources represented with red triangles. Galactic sources, namely pulsars from the ATNF Pulsar Catalogue (light gray) (Manchester et al., 2005) and all Galactic sources detected by CHIME/FRB's realtime pipeline (dark gray) are shown (Good et al., 2021). We do not plot, however, sources from lines of sight with very high emission measure as measured by Planck (Planck Collaboration et al., 2016) to avoid higher-than-representative DMs due to contamination by H2 regions and other small scale, local structure. Similarly, sources with declination $< -11°$ are not plotted as they are outside of CHIME/FRBs field-of-view, such that longitudinal variation is comparable between the Galactic and extragalactic samples. Representative positional errors are shown for sources in the top gray band. The DM errors of the FRBs are much smaller than the markers so we do not plot them. A clear gap in DM is visible between the triangles and stars. The total expected Galactic contribution to the DM from the two Galactic free electron density models, NE2001 and YMW16 are plotted in blue and pink respectively, where the shaded regions bounded by solid lines represent the range in values for lines of sight which vary with Galactic longitude (Cordes & Lazio, 2002; Yao et al., 2017). The pink, yellow, and blue dotted lines show the median value of the YMW16, Ocker et al. (2020), and NE2001 respectively at each Galactic latitude. The implied DM of the WIM disk component as a function of Galactic latitude found by Ocker et al. (2020) is shown in yellow. Four simple boundary models of $\mathrm{DM_{Gal}}$ are shown, which display the most conservative estimates supported by CHIME/FRBs extragalactic DM sample, using different fitting methods and polynomial

Jim Cordes
Cornell University

Abstract

Plasma Mirrors, Sad Trombones, and Aperiodic Fast Radio Bursts

While long-period activity windows of weeks to months have been identified in two repeating FRBs, the general absence of fast periodicities ($\sim$ sub-second to tens of seconds) is notable, especially given the high burst rates up to 100 hr^{-1} in a few cases. Bursts from repeaters often show the non-dispersive frequency drifts that are negative, $d\nu/dt < 0$ that are also distinctive. In recent work with Ira Wasserman and others, it was shown that free precession could prevent detection of an underlying spin periodicity in low-rate burst trains extending over days to months but would not deter periodicity detection in high-rate sequences. To mask such periodicities, arrival time variations greater $\sim P_{\mathrm{spin}}/3$ are needed and we suggested emission altitude variations up to the light-cylinder radius $r_{\mathrm{LC}} = cP_{\mathrm{spin}}/2\pi$ as one such cause.

As an alternative, I have been making a preliminary study of the role of plasma mirrors in the local environment of the central engine (which I take to be a young magnetar). Reflections off such mirrors cause propagation distances to lengthen, most likely stochastically, and a moving mirror will Doppler shift emission from the source to higher or lower frequencies. Multiple reflections will increase both the propagation arrival times and Doppler shifts. If mirrors tend to move away from the source, apparent drift rates between multiple reflected bursts can show the observed trend with $d\nu/dt < 0$ and at the same time erase any imprint of the spin periodicity in observed burst sequences.

While a real model is not yet developed, ideas about source and mirror configurations include: (1) opening of propagation channels by high-intensity beamed flares that drive through a surrounding nebula nonlinearly, allowing radio bursts to propagate and reflect off of channel walls; (2) fragmentation of the nebula (or channel walls) into ‘island’ mirrors with differential motions that provide multiple propagation paths. Motion of the source relative to a surrounding nebula (e.g. from a velocity kick or orbital motion) may be involved with making mirrors that recede from the source in order to get negative frequency drifts. Next steps include calculation of reflection and transmission coefficients through mirror structures. An intriguing possibility is that polarization-dependent reflections (or transmissions) can alter the polarization state of the source’s emission. This may favor one of the polarization states to reach an observer, perhaps accounting for the constancy of polarization angles across bursts in some cases.

Bio: I have been a professor in the Astronomy Department at Cornell since 1979 and a member of the Cornell Center for Astrophysics and Planetary Science. My interests include neutron stars manifested as pulsars, magnetars, and fast radio bursts and their effects on local environments, such as pulsar wind nebulae. Propagation effects in plasmas near and far (IPM, ISM, IGM, CGM) and from gravity are a long-time focus of my research. As well as providing information about the media themselves, I have worked on the characterization and mitigation of plasma dispersion and scattering for precision pulsar timing required for the NANOGrav collaboration's goal of detecting and exploiting parsec-wavelength gravitational waves. My observational work is primarily at radio wavelengths but recently has included *in situ* measurements from the *Voyager* spacecraft. I develop and use a variety of signal processing and statistical inference methods and am currently exploring various machine learning methods. Propagation phenomena seen from pulsars are also relevant to SETI, another area that I have worked in and expect to continue. Our group at Cornell is engaged with the DSA-2000 (Deep Synoptic Array) project for our interests in NANOGrav and FRBs and the GREX (Global Radio Explorer) project as a means for detecting local FRBs. Finally I am writing a book *Astro-optics of the Magnetoionic Universe* that will cover the physics and empirical aspects of propagation effects and their application to precision pulsar timing, FRBs, and SETI and other contexts.

“Plenty of Room at the Bottom”: Fast Radio Bursts in our Backyard

Abstract & Self-Introduction for Emmanuel Fonseca (WVU)
10–11 October 2022, Cornell University

Title: FRB Morphology as a (Possible) Indicator of Multiple Populations

Abstract: The increasing population of repeating fast radio burst (FRB) sources continues to highlight striking emission behavior. Specifically, repeating-FRB sources often exhibit band-limited, “downward-drifting” features in their dynamic spectra that appear to be distinct from known Galactic pulsars and magnetars. With many hundreds of FRBs now observed, it is gradually becoming clear that the FRB population can be delineated based on morphologically “simple” and “complex” structure, with all confirmed repeating-FRB sources falling into the latter category. This circumstance poses a series of interesting questions regarding the existence of multiple populations, choices in characterization of FRB morphology, morphology-based classifications of source types, and the weighting of follow-up observations of possibly repeating FRB sources.

Pleunis et al. (2021, ApJ, 923, 1) performed a comprehensive morphological study of the first source catalog produced by the Canadian Hydrogen Intensity Mapping Experiment (CHIME) FRB project. All FRBs in the first CHIME/FRB catalog were modelled assuming a running power-law form for the spectral energy distribution, as well as an intrinsically Gaussian temporal shape. While arbitrary, this parameterization is flexible to burst shapes that reflect either power-law or Gaussian spectral energy distributions. The best-fit estimates of spectral parameters and burst widths yield phases spaces that show statistically significant separations between confirmed repeating FRBs and apparently non-repeating FRBs. A summary of these differences is shown in Figure 1 below.

While instrumental biases and off-center detections can impact the observed morphology, these selection effects impact all signals detected by CHIME/FRB and thus the observed differences in distributions are believed to be astrophysical in origin. Whether the variations in morphology reflect differences in source environments, progenitor types, or orientation is the subject of debate.

The growth of the overall FRB catalog and discovery of new repeating FRBs, each with extreme morphological and polarimetric properties, have only strengthened the apparent differences in parameter distributions. Concurrently, recent FRB results have generated interest in searching for Galactic analogs of FRB sources. While the existing pulsar literature has pointed towards simple power-law forms of the spectral energy distribution, renewed probing of single-pulse morphology in various Galactic environments may bare

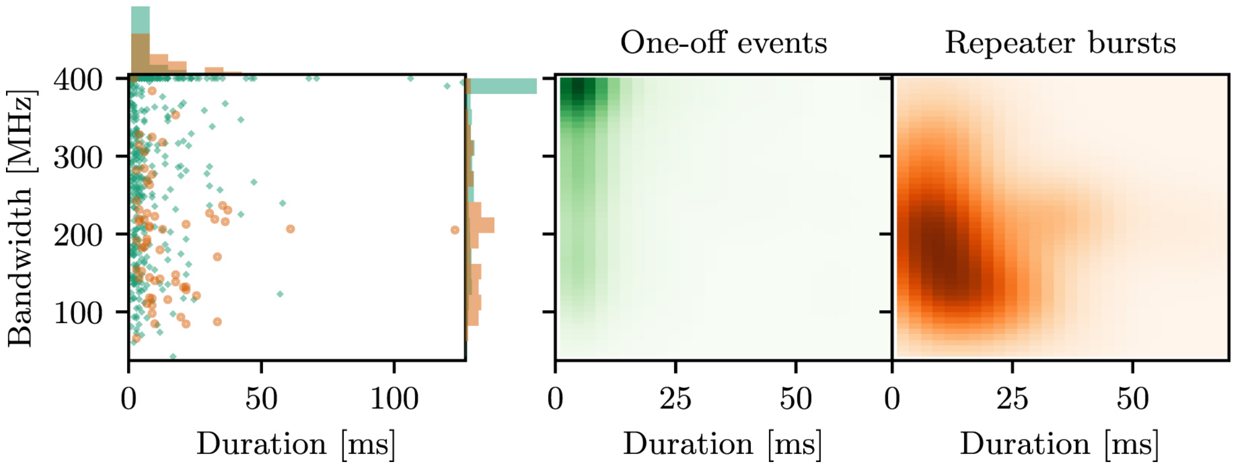

Figure 1: The distribution of FRB widths in time and frequency as evaulated for CHIME/FRB detections, which are performed in the 400-800 MHz range.

fruit in possible morphological associations with FRB sources. Galactic sites of recent interest include magnetars, pulsars within supernova remnants, binary pulsars with main-sequence companions, and "rotating radio transients."

In my talk, I will describe FRB morphology from an observational perspective and initially compare historical analyses of noted pulsars with current FRB results. I will then describe the methods used by the Canadian Hydrogen Intensity Mapping Experiment (CHIME) FRB collaboration to characterize morphology in a uniform manner. Finally, I will highlight student-led results that collectively yield features in spectro-temporal phases spaces that may be used for a variety of observational and theoretical purposes.

Self-Introduction: I currently work as an assistant professor at WVU, specializing in observational pulsar and FRB astrophysics as well as telescope instrumentation. Prior to joining WVU in late 2021, I worked as a postdoctoral researcher in Prof. Vicky Kaspi's group at McGill University in Montréal, Québec, Canada, from late 2016 till early 2021; during these years, I helped create the software and hardware that comprise the CHIME/Pulsar and CHIME/FRB backends. I previously attended the University of British Columbia from late 2010 to late 2016, where I obtained my Ph. D in astronomy under the mentorship of Prof. Ingrid Stairs; I joined the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) during my graduate career, and continue to work with NANOGrav colleagues on a variety of efforts. Before moving to Canada, I attended the Pennsylvania State University for my baccalaureate studies, from 2006 till 2010. I was born and raised through the public education system in Malden, Massachusetts, to where my parents immigrated from Bogota, Colombia. I love listening to, playing, and creating music, and enjoy learning about the histories of conflict and progress.

Jason Hessels (University of Amsterdam & ASTRON)

Hi! ☺ I'm a Professor at the University of Amsterdam's Anton Pannekoek Institute (API) and Chief Astronomer at the Netherlands Institute for Radio Astronomy (ASTRON). I have over 20 years of experience studying pulsars[1-3] and fast radio bursts[4-7] (FRBs), and I lead the AstroFlash team with about 15 students and researchers at UvA/API, ASTRON, and the Joint Institute for VLBI ERIC (JIVE). Together we are exploring the transient radio sky on timescales of seconds down to nanoseconds, and are currently focusing on:

- Pinpointing FRB locations on milliarcsecond angular scales to study their local environment[8-10]. Here we use an *ad-hoc* array of European VLBI Network (EVN) dishes as part of the PRECISE project.
- Searching for FRBs on timescales of microseconds, or less, to understand their emission mechanism and to explore the transient phase space[11-13]. Here we use voltage data from EVN dishes, the Nançay Radio Telescope (NRT), and archival data from, e.g., the Green Bank telescope.
- Ultra-high-cadence monitoring to explore the highest FRB energies as well as FRB-like sources in our own Milky Way[14,15]. Here we use the 25-m and 32-m dishes at Westerbork, Onsala and Toruń.
- Low-frequency FRB observations to understand their spectra and local environment via propagation effects[16,17]. Here we use the Low-Frequency Array (LOFAR) and NenuFAR.

Charting new phase space for FRB-like flashes
(also on behalf of Kenzie Nimmo & AstroFlash)

FRBs are signposts of extreme astrophysical environments[18-20]. They provide a novel and unique way to study the extremes of the Universe and to probe the intervening magneto-ionised material. We have only just begun exploring their scientific utility. Though magnetars are certainly responsible for some fraction of the observed FRBs[21,22], the diverse properties and locations of FRBs suggest that this is far from the complete answer[10,23]. Rather, we are confronted with a rich and multi-faceted puzzle with proposed links to other extreme astrophysical phenomena like super-luminous supernovae[24], compact object mergers[25,26], and relativistic shocks[27]. In the coming decade, we should aim to greatly expand the parameter space we are searching for fast radio transients.

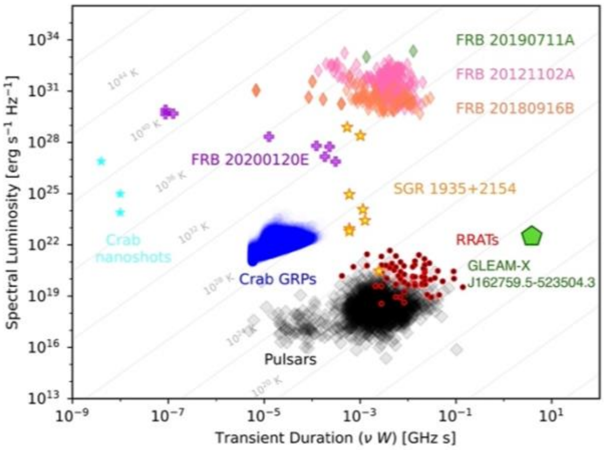

Figure 1: The 'fast transient parameter space' of spectral luminosity vs. transient duration. Pulsars, giant pulses, magnetar radio bursts and FRBs span 18 orders-of-magnitude in spectral luminosity and 8 orders-of-magnitude in timescale. Diagonal grey lines show the implied brightness temperature. The magnetar SGR 1935+2154 produces bursts that span 8 orders-of-magnitude in spectral luminosity – bridging Galactic pulsars and extragalactic FRBs[14,21,22]. The globular cluster FRB 20200120E makes bursts that are tens of nanoseconds up to milliseconds. The recently discovered[28] GLEAM-X J162759.5–523504.3 demonstrates the parameter space that can still be explored on timescales of seconds. *Adapted from Nimmo et al. (2022).*[12]

The seminal discoveries of pulsars[29] and FRBs[30] were both enabled by opening new parameter space in terms of the range of timescales, luminosities, electromagnetic frequencies and event rates we can observe. The currently known sample of fast radio transients span timescales of nanoseconds to seconds and over 18 orders-of-magnitude in spectral luminosity (Figure 1). FRBs have been detected at radio frequencies of 110 MHz[16] up to 8 GHz[31] (over 6 octaves) and with rates from hundreds per hour to only 1 burst per hundreds of hours of observation. The diverse properties of the known FRBs strongly suggest that we have still only scratched the surface of what is out there to find. Repeating and non-repeating FRBs have statistically different properties and may come from physically distinct progenitors[23]. At the same time, oddball FRBs like a 3-s event showing periodic peaks spaced at 217 ms[32], and an exceptionally faint FRB hosted in a globular cluster[10], are also hinting at a rich variety of source types and environments. Dozens of FRB theories have been proposed[33], with both a range of progenitor types and emission mechanisms investigated. I argue that we have every reason to believe that nature is highly creative and that it produces a diversity of FRB emitters beyond just the proven example of magnetars. To quote a colleague working on FRB theory: "radio bursts are cheap" (in terms of their energetics), and hence they can be expected in many different contexts. FRB models often invoke neutron stars or black holes, to satisfy the energy density requirements imposed by the luminosities and durations of FRBs. However, neutron stars and black holes come in many varieties and astrophysical contexts; there is yet no consensus on which of these can generate FRBs.

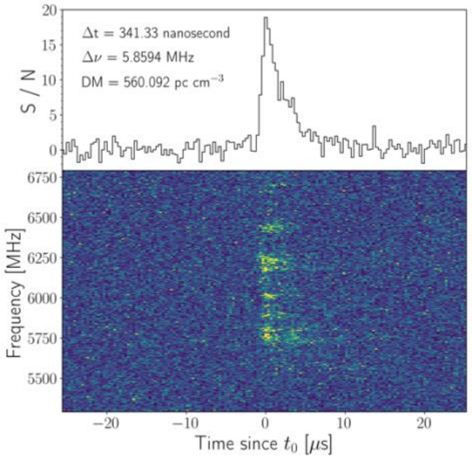

Figure 2: An isolated 5-microsecond-wide burst from the repeater FRB 20121102A. Note that the time resolution is 341 nanoseconds[13].

Discovering populations of ultra-fast radio bursts (uFRBs) and ultra-young, obscured FRBs: Work by my group and others has demonstrated that not only can FRBs exhibit (sub-)microsecond structure, but that there are also radio bursts whose *entire duration* is only a few microseconds (Figure 2). Current FRB searches are mostly blind to such events because they use relatively coarse sampling time (0.1 – 1 ms) and low radio frequencies (< 2 GHz), where scattering from the Milky Way foreground and other intervening plasma limits the effective time resolution. My goal is to create a wide-field radio telescope system operating at ~5 GHz which will allow the first untargeted search for (sub-)microsecond uFRBs. Such a system could conceivably be created using dense-packed arrays of 1-m commercial satellite dishes equipped with low-noise ambient temperature amplifiers and piggybacking on the infrastructure of the LOFAR and/or CHIME/FRB Outrigger and CHORD sites. The goal is to discover a new, physically distinct class of FRB-like emitters whose exceptionally short-duration bursts provide unparalleled probes of the intervening magneto-ionic medium and gravitational lensing effects. At the same time, the high observing frequency will allow us to peer into dense star-forming regions and galactic center environments, where a large population of young FRB sources may exist. Current low-frequency searches are insensitive to this population.

Discovering a population of not-so-fast radio bursts (nsFRBs): Conversely, recent discoveries like the 18-min transient GLEAM-X J162759.5–523504.3 (Figure 3), with its 10s of seconds bursts, are showing us that there is a population of much longer-duration FRB-like signals to be discovered. Low-frequency radio interferometric telescopes are well poised to open this parameter space because they can effectively separate these signals from human-made interference using both dispersive delay and spatial filtering. My goal is to discover this population of nsFRBs by developing fast imaging (10ms visibilities) capabilities for LOFAR in the coming years and then for the Square Kilometre Array (SKA) Low telescope on the timescale of 5-10 years. The putative population of nsFRBs could stem from, e.g., ultra-long-period magnetars, white dwarf pulsars, and nearby flare stars.

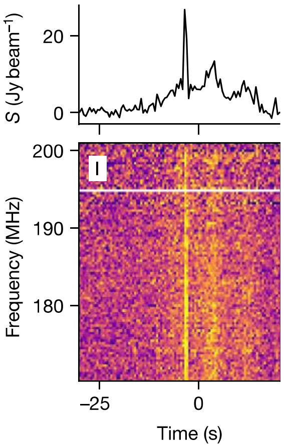

Figure 3: A dynamic spectrum and frequency-integrated burst profile of the MWA-discovered transient GLEAM-X J162759.5–523504.3. The remarkable brightness and tens of seconds duration of this source place it in a previously unpopulated part of the fast transient parameter space (see also Figure 1). *From Hurley-Walker et al. (2022).* [28]

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Fireball in Fast Radio Bursts

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ABSTRACT

A fireball of radiation plasma created near the surface of a neutron star (NS) expands under its own pressure along magnetic field lines, and produces photon emission and relativistic matter outflow. We comprehensively classify the expanding fireball evolution into five cases and obtain the photospheric luminosity and the kinetic energy of the outflow, taking into account key processes; lateral diffusion of photons escaping from a magnetic flux tube, effects of strong magnetic field, baryon loading from the NS surface, and radiative acceleration via cyclotron resonant scattering, some of which have not been considered in the context of gamma-ray bursts. Applying our model to magnetar bursts with fast radio bursts (FRBs), in particular the X-ray short bursts from SGR 1935+2154 associated with the Galactic FRB 20200428A, we show that the burst radiation can accelerate the outflow to high Lorentz factor with sufficient energy to power FRBs.

We also investigate parametric decay of a circularly polarized Alfven wave propagating along a constant magnetic field in a relativistic magnetohydrodynamical (MHD) plasma. Perturbative analyses are performed in the fluid comoving frame, forcusing on the case that the Alfvén velocity is larger than the sound velocity, even up to relativistic one, i.e., high σ (ratio of the magnetic to matter energy density). We find that the dispersion relation possess an unstable mode that parent Alfvén waves decay into forward-propagating acoustic waves (longitudinal slow MHD waves) and backward-propagating Alfvén waves, for any σ but with suppressed by $\sigma^{-1/2}$ at high σ. The acoustic waves shortly become nonlinear, leading to shock dissipation. We discuss implications for FRBs including that Alfvén waves preferentially heat high density plasma, boosting a fireball that transfers the kinetic energy along a magnetic field line to the FRB emission site.

1. SELF-INTRODUCTION

Research: Theoretical astrophysics (Gamma-ray bursts, Fast radio bursts, Electromagnetic counterparts to gravitational waves, High energy neutrinos, Gamma-rays, Cosmic rays, etc.)

Education: Ph.D. in Physics, Kyoto University, Japan (Mar. 2001)
M.S. in Physics, Kyoto University, Japan (Mar. 1998)
B.S. in Physics, Kyoto University, Japan (Mar. 1996)

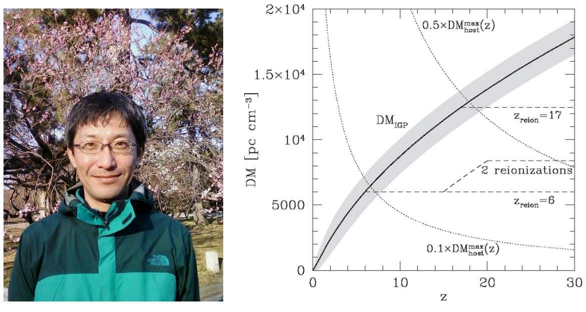

Figure 1. I may be known for the DM-z plot in Ioka (2003).

Positions: JSPS fellow, Department of Earth and Space Science, Osaka University, Japan (Host: Prof. Fumio Takahara; Apr. 2001)
Postdoctoral fellow, Physics Department and Center for GravitationalWave Physics, Pennsylvania State University (Host: Prof. Peter Mészáros; Apr. 2004)
Assistant Professor, Department of Physics, Kyoto University (Apr. 2005)
Associate Professor, Institute of Particle and Nuclear Studies, KEK (Oct. 2007)
Professor, Yukawa Institute for Theoretical Physics, Kyoto University (Feb. 2016)

Papers: "The Cosmic Dispersion Measure from Gamma-Ray Burst Afterglows: Probing the Reionization History and the Burst Environment", Ioka (2003)
"Cosmological Fast Radio Bursts from Binary White Dwarf Mergers", Kashiyama et al. (2013)
"A Binary Comb Model for Periodic Fast Radio Bursts", Ioka & Zhang (2020),
"Fast Radio Burst Breakouts from Magnetar Burst Fireballs", Ioka (2020)
"Binary Comb Models for FRB 121102", Wada et al. (2021)

YITP has some visitor programs. Please let me know if you are interested.

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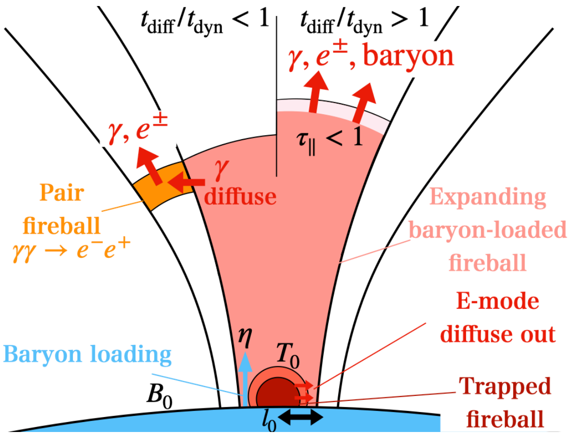

Figure 2. A fireball expanding along magnetic field lines releases radiation for X-ray bursts and generates the kinetic energy for FRBs.

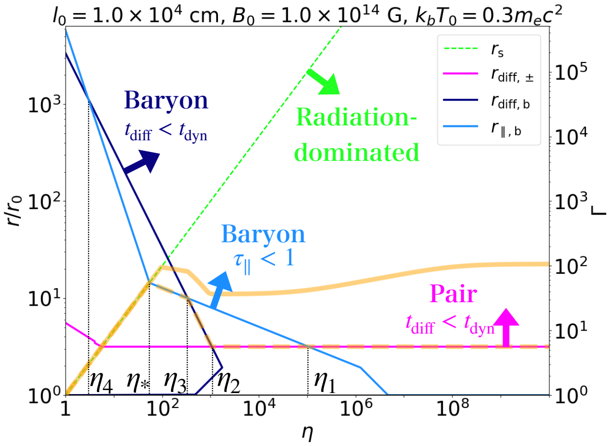

Figure 3. The characteristic radii (normalized by the stellar radius) and Lorentz factor of an outflow with dimensionless entropy η. The maximum Lorentz factor (*orange thick line*) is $\Gamma \sim 10^2$.

2. EXPANDING FIREBALL

How is the energy transferred to the emission region of FRBs? In a magnetar model, the energy is most likely generated on the surface of a neutron star. On the other hand, the emission region is thought to be far up in the magnetosphere or even outside it. There are basically two ways of energy transfer: kinetic flux and Poynting flux.

In the Galactic FRB, the X-ray bursts were $\sim 10^3$ times brighter than the FRBs. The X-ray bursts are the main and the FRBs are the sub. We should first explain the X-ray bursts, and in that framework, the FRBs should be modeled.

We show that a fireball that explains the X-ray bursts can also produce enough kinetic energy for the FRBs (Wada & Ioka 2022). An easy way is to mix baryon. Even without baryon, the radiative acceleration beyond the photospheric radius via resonant cyclotron scatterings could achieve this.

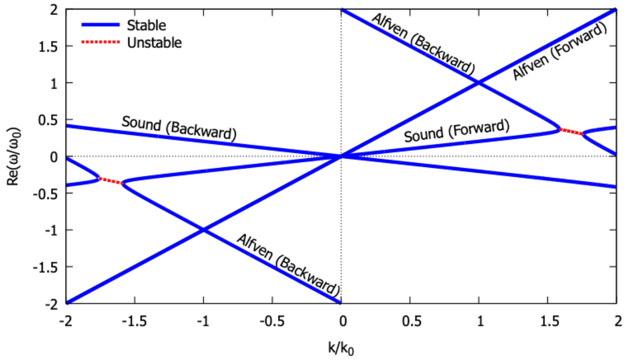

Figure 4. The dispersion relation that shows the instability. The frequency has an imaginary part at the red dotted line.

3. DECAY OF ALFVÉN WAVES

The energy is also transferred by Poynting flux, in particular Alfvén waves. In the solar physics, Alfvén waves play an important role in the coronal heating and wind acceleration. We extend the analogy to relativistic MHD plasma.

Ishizaki & Ioka (2022) find the decay rate at high σ and low temperature is about

$$\frac{\omega_i}{\omega_0} \sim \frac{1}{2}\frac{\delta B}{B}\left(\frac{v_A}{c_s}\right)^{1/2}\sigma^{-1/2}, \qquad (1)$$

which implies that the Alfvén waves could decay in a fireball. We could not find a paper that derived this simple formula, but we may miss it. Please let us know the relevant papers.

I would like to thank S. Kulkarni for letting me know my misunderstanding about the format of this summary.

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Wada, T., Ioka, K., & Zhang, B. 2021, ApJ, 920, 54, doi: 10.3847/1538-4357/ac127a

Title: Probing the Warm Ionized Medium (WIM) on arcsecond scales
Speaker: S. R. Kulkarni

The column density to an FRB, the dispersion measure (DM), is the most important extrinsic parameter of an FRB. The measured DM is the sum of DM within the Milky Way, in the IGM/CGM and within the host galaxy. The Warm Ionized Medium (WIM) is the primary source of DM in the Milky Way. The medium is pervasive (fill factor of 0.25, in the disk; unity in the upper and extended halo). The FRB signals also undergo scattering due to very fine structure within the WIM. Pulsars with parallax provide fundamental underpinnings to our model of the WIM. Optical observations of recombination line (primarily H-alpha) and "nebular" (forbidden) lines (primarily [NII] and [OII]; other lines such as [NI], [OII], [OIII] have not been exploited) have provided us insight into the physical properties: the WIM temperature varies between 6000 K and 10^4 K; the ionization fraction of hydrogen is 90% while the ionization fraction of helium may be as low as 0.2. The Wisconsin H-alpha Mapper (WHAM), a dual-etalon Fabry-Perot imager, is the workhorse for optical emission line studies. The angular beam of WHAM is large, about a degree in diameter.

Recall that the signal-to-noise ratio (SNR) for surface brightness measurements is proportional to the square root of the product of the collecting area, A, the beam solid angle, **Ω**, the integration time, t, and high spectral resolution, R. WHAM achieves high sensitivity by having a large beam (**Ω**=1 deg^2) and high spectral resolution (R=15,0000) and modest collecting area (60-cm siderostat). Thus, if one wants to study the structure of the WIM, on say, arcsecond scales, then one needs to increase the collecting area by large factor and increase the integration time. Alternatively, one could observe in the mid-IR where the lines are readily excited, as opposed to the optical lines which suffer are excited by a smaller population of energetic electrons. That is the approach that we took.

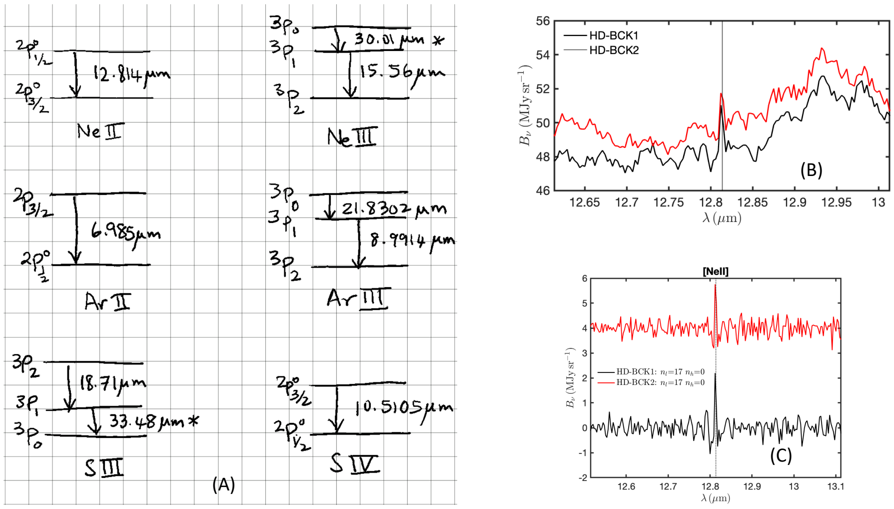

Figure 1. (A) Grotrian diagram of mid-IR fine structure lines accessible to MIRI-MRS. (B) Detection of [NeII] 12.8μm line. The two spectra are from the background field to HD166433 but taken on different days. (C) The same as in (B) but after Fourier filtering.

James Webb Space Telescope has a large collecting area, 25.4 m^2. It is equipped with two integral field unit (IFU) spectrographs. Of interest to us is the MIRI-Medium Resolution Spectrometer (MRS) which has a field-of-view of 5"x5" and operates in the 5 to 30 **μ**m. As can be seen from Figure 1A, this wavelength range includes a number of mid-IR fine structurelines. The spectral resolution is about 2000.

We downloaded Level 3 data of a calibration dataset (HD 163466; on source and background field which was observed twice). Our analysis treated the entire IFU field as a "light bucket". In that spirit,we took the median of each image slice of the 3-D IFU data cube. [NeII]12.8 micron is readily detected both in the background field (see Figure 1B) and also in the sky spectrum of HD163466 (albeit at a lower SNR owing to scattering from the bright calibration star). IFU spectrographs, whilst powerful, are infamous for the complexity in data reduction. STScI is refining the pipeline reduction for MIRI-MRS. It is clear from Figure 1B that the sky spectrum suffers from "lumpy" baselines and "fringing" (pixel-to-pixel variation). Fortunately, the expected emission from the WIM is an unresolved line. Given this expectation we applied a low-pass filter (to flatten the baseline) and a high-pass filter (to get rid of fringing). As can be seen from Figure 1C the resulting sky spectrum shows a robust detection of [NeII] emission. The inferred EM in this direction is less than 16 cm^{-3} pc, squarely in the range expected from the WIM.

We followed up with searches for other lines. From a photon-noise persepctive many other lines should be detectable. However, the present level of IFU pipeline data reduction is far from this ideal limit. We detect [SIII] and perhaps a trace of [SIV]. The expected SNR for [ArII] and [ArIII] is nominally about 10, the detection of which would require a data reduction pipeline operating at the photon noise level limit.These initial findings suggest that the diffuse EUV ionizing field incicent on the WIM is "soft" and supports the low helium ionization fraction, <0.2, inferred from radio recombination lines.

Any hour-long observation with MIRI-MRS, regardless of the intent of the proposing astronomer, will lead to detection of emission from WIM. Separately, I draw attention of the reader to the development of powerful high resolution IFU spectrographs such as MUSE on VLT and the Keck Cosmic Imager (KCI) on Keck. Take for instance, the red-arm of KCI, "Keck Cosmic Recombination Imager' (KCRM). With a photon-to-photoelectron througput of better than 0.2, a spectral resolution of better than 15,000, and $\mathbf{\Omega}$=160 arcsec^2, the instrument, in the light bucket mode, is well suited to detecting nebular lines from the WIM. As with JWST any moderately deep observation of KCI will result in detection of optical lines from the WIM. In short, we are on the verge of a new cottage industry with both JWST and Keck that will provide steady data for the study of the WIM on arcsecond scales.

This report is drawn from a paper titled "Mid-infrared fine structure lines from the Galactic warm ionized medium" by S. R. Kulkarni, C. Beichman and M. E. Ressler which will shortly be submitted to PASP.

The author. I am a professor of astronomy at Caltech but spending this Fall semester at Cornell University. My interests have evolved and also changed over time. My thesis was centered on the atomic phase of the Galactic ISM (primarily HI) and radio astronomy instrumentation. Towards end of my thesis, under the guidance of Don Backer, I discovered the first millisecond pulsar. I left the field of interstellar medium studies as soon as I obtained my PhD switching to millisecond pulsars, globular cluster pulsars and soft gamma-ray repeaters. Working with Dale Frail I showed that soft gamma-ray bursters were Galactic in origin, arising from massive stars and with some having a plerionic nebula. After this phase I switched to high dynamic range imaging at optical wavelengths and infra-red interferometry. Our group discovered the first brown dwarf (Gliese 229B). I then switched to gamma-ray bursts (GRBs) and our group showed that GRBs are of extra-galactic origin. Dale Frail and I discovered radio afterglow from GRBs. I then switched to an ambitious study of the dynamic night sky, successively developing and commissioning Palomar Transient Factory, intermediate Palomar Transient Factory and Zwicky Transient Facility (ZTF; 2017-present). My student Chris Bochenek (graduated in 2021) developed STARE2 (taking advantage of the considerable engineering development for the DSA-10 and DSA-110 projects) which detected a mega Jansky burst from a Galactic magnetar (2020). After stepping down as Director of the Caltech Optical Observatory (COO) I elected to return to the field of Galactic ISM studies. I am currently focused on the Warm Ionized Medium (WIM) and, over the next few years, hope to successively work up to the Warm Neutral Medium (WNM) and the Cold Neutral Medium (CNM).

FRB scintillation, lensing, and as probes of cosmology

Pawan Kumar

I will describe my recent work on wave scattering by magnetized plasma and conversion of linearly polarized source to partial circular polarization. Gravitational lensing of FRBs in the presence of turbulent plasma will also be discussed, and some results on how plasma scatterings might affect investigations of stellar mass objects will be presented. The potential use of FRBs to investigate the cosmic reionization history will be described. And finally, some results on FRB radiation mechanism will be shared, in particular what we can learn from the 217 ms periodicity that has been reported for FRB 20191221A .

DONG LAI

Dong Lai is Professor of Astrophysics at Cornell. He received Ph.D. in physics from Cornell in 1994, and was a postdoctoral fellow at Caltech. He joined the faculty of the Astronomy Department at Cornell in 1997. His research is in theoretical astrophysics, focusing on compact objects (neutron stars, black holes and white dwarfs), exoplanets and astrophysical (particle and fluid) dynamics in general. He is very interested in FRBs, but has only written two small papers on the subject. He has worked on several aspects of neutron star astrophysics (assuming FRBs are related to neutron stars), including equation of state, radiative transfer and neutrino transfer in magnetic neutron stars, supernova kicks, pulsar timing, accreting NSs, merging NS binaries and gravitational wave sources, etc.

A New Class of Luminous Extragalactic Radio Source

Casey J. Law

Summary

Despite an increasing array of fascinating discoveries, it is not yet clear what kind(s) of source emit FRBs. Aside from being a compelling mystery, this complicates efforts to use FRBs as probes. In the long-term, FRB science will be driven by their application to broader astrophysical problems, such as the "missing baryon problem", the search for primordial black holes, or in precision cosmology. However, these applications require interpreting the FRB dispersion measure (DM) as an extragalactic electron column density. Without knowing the nature of the FRB source or reliably classifying FRB environments, there are likely to be systematic effects that compromise their use as probes.

Two FRBs have been associated with a luminous persistent radio sources (PRS; Figure 1). These two FRBs are also known for having anomalously large DM that compromises their use as probes. The fact that both FRBs reside in low-metallicity dwarf galaxies with high specific star formation rate suggests they may represent a special formation channel or environment. However, it is not known what kind of source generates either FRBs, PRS, or why they are related. In this sense, the FRB/PRS sources represent a double mystery.

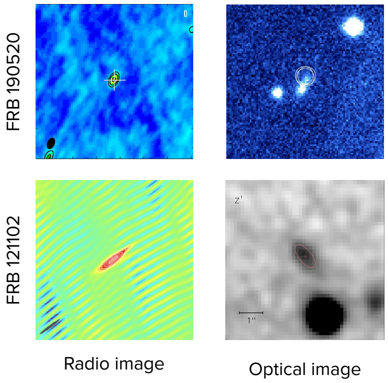

Figure 1: Grid of radio and optical images of FRBs 20121102A and 20190520B. Both are associated with PRS in dwarf galaxies.

With a luminosity greater than 10^{29} erg/s/Hz, PRS are detectable in the VLA Sky Survey at a distance of 300 Mpc. Traditionally, it has been assumed that the radio sky is composed of either star-forming galaxies and AGN. The volumetric density of PRS implies that they comprise as much as 1% of compact, luminous radio sources detected in the local universe. At this density, these sources may confound the study of AGN in the local universe. More fundamentally, they change they way we think of the extragalactic sky.

The Cornell FRB workshop theme of “Plenty of Room at the Bottom” is highly relevant to the study of FRB origins and environments. In my talk, I’ll share my analysis of the FRB and PRS populations, and efforts to identify FRB sources without FRBs (i.e., via their PRS).

Introduction

I am a Research Scientist in Caltech Astronomy and Leader of the Software and Algorithms Lab at the Owens Valley Radio Observatory. I studied at the University of Hawai‘i and received my PhD from Northwestern University in 2007. I have held positions at the University of Amsterdam and UC Berkeley and am PI of *realfast*, a fast transient search instrument integrated with the Very Large Array. My interests include transients, data intensive astrophysics, software development, and civic engagement.

My research lies at the intersection of transient astrophysics and radio survey techniques. I am leading development or collaboration with major FRB observing systems, including VLA/*realfast*, DSA-110, OVRO-LWA, and CHIME/FRB. Ongoing programs at these facilities will discover, localize, and associate FRBs to host galaxies and other counterparts. Through my involvement in the VLA Sky Survey and the DSA-2000 project, I am also developing techniques for slow radio transient science; one effort led to the discovery of a likely orphan afterglow of a long GRB.

The magneto-environment of FRBs and potential evidence for binary

Dongzi Li

Bio Dongzi Li is a Sherman Fairchild Postdoc Research Associate at Caltech. She obtained her Ph.D at the University of Toronto with prof. Ue-Li Pen. Currently, she mainly studies FRBs and pulsars, but she is also interested in cosmology. Her research highlights include the discovery of the long-term periodicity of an FRB, the study and modeling of polarization effect on pulsars and FRBs and the kinetic SZ effects on CMB.

Abstract The discovery of FRB-like bursts from a Galactic magnetar, SGR 1935+2154 (2; 3), suggests that magnetars could be the progenitor of at least some FRBs. However, it is still unknown if all FRBs are produced by magnetars. Polarimetry is a powerful probe for understanding the circum-burst environment. Unlike ordinary pulsars, a significant fraction of FRBs has Faraday rotation measures (RMs) much greater than the value of typical line-of-sight in a galaxy (e.g. (12)). Moreover, five out of six FRBs with more than two published RMs are observed to have siginificant RM variations (11; 6; 13; 17; 1; 4). Two of them with a large number of measurements show order one non-monotonic RM change within a few months(4; 1; 17) (Fig 1). Given the typical velocity of a neutron star, it maps to a spatial scale of only AU, much smaller than the spatial scale of supernovae remnants (close to pc). FRB 20201124A, which is ~ 600 pc away from the nearest bar/spiral arms(17), is shown to have at least two regions of highly varying RMs with opposite signs (Fig 1). The large and non-monotonic variation of RMs is not observed in normal magnetars (unless it locates near the galactic center). It is possible to explain it with the presence of a highly turbulent young supernovae remnant(4; 18), although the large offset from the star forming region can be a challenge. The quick RM change is relatively easy to achieve with the existence of a companion. We observe similar polarization properties in a globular cluster pulsar binary system PSR B1744-24A (10) (Fig 2). It shows significant, irregular, short-time variations of the RM at random orbital phases, depolarization, as well as rare propagation effects limited to highly magnetized environment, such as Faraday conversion and polarized attenuation. Similar polarization behavior can be achieved with massive companion at larger distance. For example, large RM variation has also been observed in a pulsar with Be star binary(7).

Apart from the similarity in observed polarimetry, there is other independent evidence suggesting that some FRBs reside in binary systems. FRB 20180916B is observed to have a 16-day period (16), while FRB 20121102A potentially has a periodicity of 160 days(14). Binary orbits have been proposed as origins for these long-term periodicities. Moreover, the increasing localization of FRBs shows a wide range of host galaxies with no preference for high star formation rate (5). The nearest extra-galactic FRB is localized to a globular cluster(9), where pulsar binaries are common. Moreover, for the few nearby FRBs that are localized to spiral galaxies — similar to the Milky way, they are observed to offset few hundred pc from the nearest star-forming region(15; 17). This large offset contrasts with the distribution of the galactic magnetars, which have a typical scale height of 20-30 pc from the galactic plane (8). Assuming the offset results from the progenitor moving away from the birth spot, it suggests progenitors of older age than magnetars but consistent with binaries.

Shortly, more localized FRBs, and an increased number of nearby FRBs will help us further understand the progenitor. Apart from that, two other directions can also be helpful. 1. Searching for rare polarized effects at different frequencies. Special LOS can be manifest through polarization study. In the case of PSR B1744-24A, the DM/RM variation and eclipses can all appear at random phases. However, the changes in V are only observed when the LOS approaches the companion (Fig 2 bottom right panel), revealing the orbital period. 2. Dedicated

search for globular cluster (GC) FRBs. The M81 GC FRB is the black sheep that's unlikely related to the normal magnetars. We will need more samples to estimate the fraction of the population and understand the progenitor. Nearby massive ellipical galaxies, such as M87, which compose 50X more GCs than the total GCs to the distance of M81, will be great targets for follow-up observation.

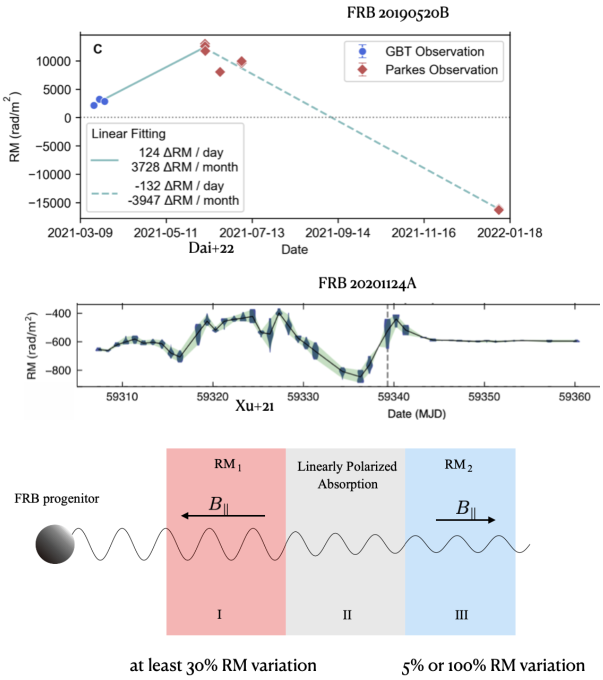

Figure 1: (Top two panels) The non-monotonic RM variation of two repeaters(4; 17); (Bottom panel) The highly variable multi-layer medium near the FRB 20201124A.

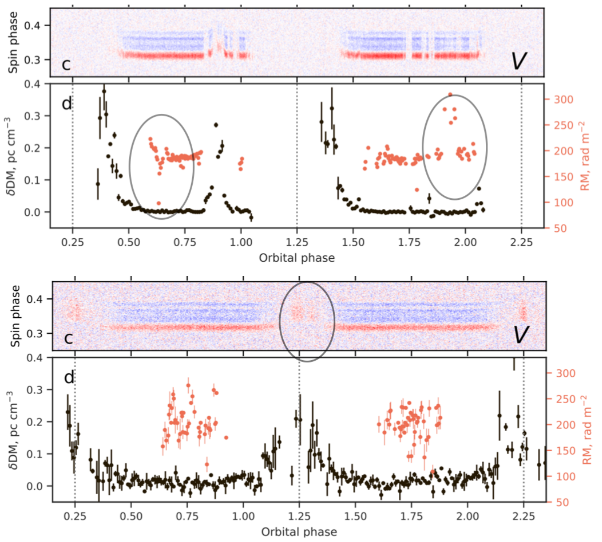

Figure 2: Highly variable PSR B1744-24A polarization versus orbital phase. The upper panel of each figure is the circular polarization (V), with red and blue indicating different signs. The lower panel is the variation of RM (red) and DM (black). Irregular, fast variations of RM are seen at random orbital phases due to the magnetized plasma from the companion. The change of V is seen when the LOS approaches the companion.

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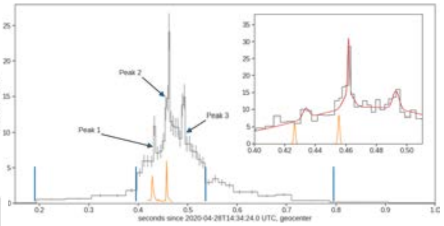
Wenbin Lu
Assitant Professor of Astronomy, UC Berkeley

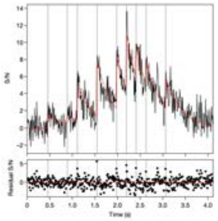
Wenbin Lu received his PhD in astronomy from University of Texas at Austin in 2018. Wenbin was a postdoctoral fellow at Caltech and then at Princeton University before joining the University of California Berkeley as an assistant professor in 2022. Wenbin's research is focused on the theoretical understanding of high-energy astrophysical transients, including fast radio bursts, tidal disruption events, and compact object mergers.

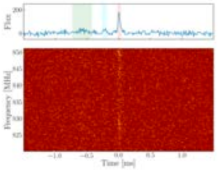
Whence to FRB - Maxim Lyutikov (Purdue)

1. FRBs are magnetospheric

- Temporal coincidence X-ray-radio
- magnetar association
- Radio leads X-ray
- frequency drifts
- PA swings
- periodicity
- micro-nano structure

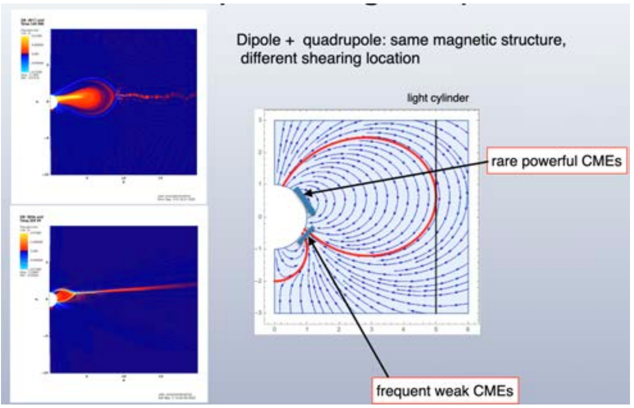






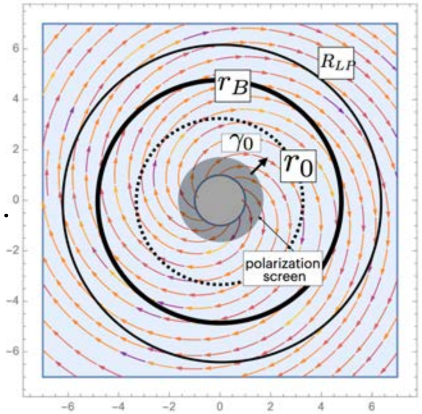
2 Where to shear the footpoints

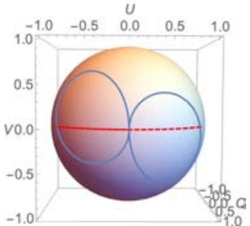
- Solar flares paradigm.
- What matters are:
  - size of active region
  - value of B-field
  - Hall shearing rate ~ B^2
  - **location of shear**
    - do field lines extend far o
    - or close near the star?


Dipole + quadrupole: same magnetic structure, different shearing location

3 Polarization: Faraday conversion in the inner wind

- Pair plasma screen of DM= 10^{-6} pc cm^{-3} can give large Pi-transformation!
- Can produce
  - Large Circular
  - Large RM, with changing signs
- non-standard $RM \propto \lambda^{\alpha}, \alpha \neq 2$
- RVM+ Π-conversion: tracks on Poincare sph.





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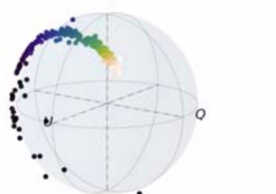
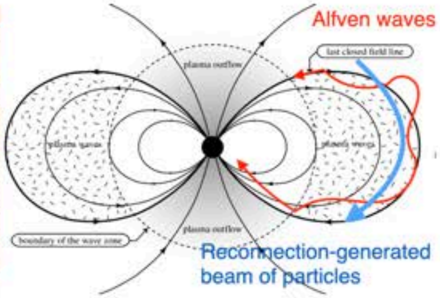
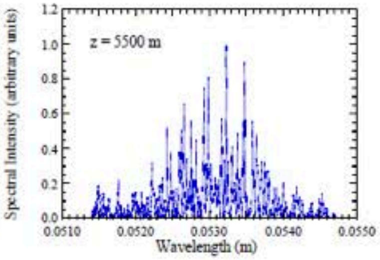


4. Emission mechanism: Free Electron Laser

- Guide-field dominated regime
- Alfven waves in the magnetosphere (wiggler)
- **Reconnection-driven** beam of charged particles
- bunches induced by wiggler emit collectively
- E.g. narrow line with pulse sub-structure





5. Maxim Lyutikov (Purdue U.)

- M.S. magna cum laude, Theoretical Physics, 1992, *Moscow Engineering Physics Institute*, Moscow
- Ph.D., Theoretical Astrophysics, 1998 , *California Institute of Technology*, Pasadena, CA
- Professor, Purdue Department of Physics and Astronomy (assistant, associate, full, 2006 -)

- Research topics: Plasma astrophysics, compact objects

- Synergistic Activities: *Plasma 2020*, panel member

Solving Feedback with Electron Power Spectrum Measurements from FRBs

Kiyoshi Masui

Galaxy formation is among the most active areas of research in astrophysics, and the hardest problem in galaxy formation is feedback. Feedback is a catch-all term for processes that regulate or cut-off star formation, with the two dominant forms being supernovae (SN) feedback and active galactic nuclei (AGN) feedback. In SN feedback, the death of newly formed stars inject both thermal energy and momentum into the surrounding gas, heating it, ejecting it from the galaxy and thus removing the fuel for further star formation. Similarly, in AGN feedback, accretion of gas onto super-massive black holes can produce both radiation (that heats surrounding gas or prevents it from cooling) and high-power jets that launch gas over great distances.

Coming to a quantitative understanding of feedback is exceptionally difficult. One reason for this is the complicated and diverse range astrophysical processes involved. Another is the wide range of physical scales—the accretion that powers AGN feedback operates on scales smaller than a parsec, and yet the effects of a single black hole can be felt over distances of megaparsecs. For this reason, feedback cannot be simulated from first principles, and large-scale simulations of galaxy and structure formation must invent “sub-grid” prescriptions that emulate the effects of these processes at the resolution scale.

Furthermore, feedback is poorly constrained observationally. The primary effect of feedback is to heat and eject gas from galaxies, however, the diffuse warm-hot gas in the intergalactic medium (IGM) is difficult to observe directly. As such, sub-grid models must be calibrated to observations of feedback’s secondary effects—the impact on star formation rather than the gas distribution. This is, in essence, the missing-baryon problem familiar in the fast radio burst (FRB) field: the exact location of the majority of the universe’s baryons can neither be reliably simulated nor directly observed.

Fast radio bursts present a unique opportunity to directly measure the spatial distribution of the IGM, as traced by dispersion-inducing free electrons [1, 2]. Cross-correlating (or stacking) dispersion measurements on foreground galaxy locations provides a measurement of the mean galaxy electron profile. Such an analysis has already been performed by Connor and Ravi [3] for the closest (< 40 Mpc) galaxies and FRBs from the first catalog from the Canadian Hydrogen Intensity Mapping Experiment Fast Radio Burst (CHIME/FRB) project [4]. This resulted in a measurement of the gas associated with these galaxies on radial scales of ~ 200 kpc.

The analogous measurement performed in Fourier space (which is equivalent in information content) measures the electron–galaxy cross-power spectrum $P_{eg}(k)$ [5]. This quantity is also readily measured in cosmological simulations, making direct comparisons between observations and models straight forward. Simulations implementing different sub-grid feedback models make predictions for the cross-power that differ in amplitude and shape by order unity for wave numbers $0.1\ h/\mathrm{Mpc} < k < 10\ h/\mathrm{Mpc}$. Nicola et al. [6] showed that such statistics are highly informative of feedback physics. Furthermore, opportunities to cross-correlate FRB dispersion with different galaxy sub-samples could provide yet more information. For example, AGN feedback is expected to dominate in the environs of brightest cluster galaxies, whereas SN feedback should dominate in the field. Pessimistically, a precise measurement of $P_{eg}(k)$ will “solve” feedback in the empirical sense—it will provide an observational constraint on functions that are highly sensitive to the sub-grid model. In matching these observations, the model will have little leeway and will thus be fixed. More optimistically, such tight constraints will provide new insight into the underlying astrophysics, solving the problem in a more satisfying way.

Compared to other analyses employing dispersion to study diffuse gas, cross-correlating with galaxies is both highly quantitative (in that it can be compared directly to simulations) and robust to systematics. In other analyses, the ambiguity how much dispersion is contributed by the FRB host (and to a lesser extent the Milky Way) muddies any interpretation. In contrast, in cross-correlation only the dispersion contributed from electrons spatially correlated with the galaxies contribute. Other electron structures add noise, but not bias, which can be overcome with a larger sample.

The observational prospects for this measurement are bright. CHIME/FRB is currently accumulating a sample of hundreds of "baseband" localizations with few-arcminute precision. Such localizations are sufficient to reach the scales of interest (∼Mpc) for foreground galaxies closer than 1 Gpc, corresponding to a redshift range for which there are several galaxy samples to correlate against. In roughly a year, the CHIME/FRB Outriggers project will start producing host associations and source redshifts for CHIME-detected FRBs. This will enable subtraction of the redshift-dependent mean dispersion and remove ambiguity about whether the FRB is in front or behind the galaxy, thus eliminating major sources of noise. Ultimately, Madhavacheril et al. [5] forecast a that a sample such as that to be collected by CHIME/FRB Outriggers will enable better than 10% measurements of $P_{eg}(k)$ over two decades in scale.

About Me

I am an Assistant Professor of Physics at MIT and a member of the CHIME/FRB team. I started my career as a theoretical cosmologist but soon transitioned to observation, working with the hydrogen intensity mapping survey at the Green Bank Telescope (GBT). I became interested in FRBs when (at nearly the same time) I started thinking about using them to map large-scale structure and one was detected in the GBT survey data. That FRB was only the second to be detected at a telescope other than Parkes; the first for which Faraday rotation was measured; and, from the two-screen scattering properties, was the provably extragalactic in the era before direct host associations.

I joined the CHIME team early in its development and have worked on instrumentation and analysis, particularly calibration and statistical inference. I led the deployment of the triggered baseband recording system and have been involved in many of the results coming out of CHIME/FRB, including the first catalog release. I currently spend most my time on the commissioning effort for the CHIME/FRB Outriggers in my role as Project Scientist.

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Introduction: Brian D. Metzger

I am a professor at Columbia and researcher as the Flatiron Institute. I have long standing interests in the central engines of energetic transients: gamma-ray bursts, superluminous supernovae, stellar mergers (both degenerate and non-degenerate), tidal disruption events, and now fast radio bursts. My interest in FRBs started with immediate intrigue in the local-scale environment of FRB 121102, particularly the luminous persistent synchrotron radio source and high rotation measure of the bursts. To me, this immediately suggested that this highly-active FRB engine was embedded in a young nebula energized by the same activity responsible for creating the bursts. As someone deeply familiar with models for gamma-ray bursts and luminous supernovae from newly-born magnetars, I was immediately drawn to magnetars as an FRB source population (though realizing the putative magnetars responsible for repeating FRBs need be far more extreme and active than those in the Galaxy, cautioning against generalizing too much from the Galactic population).

However, despite vindication of this idea coming with the incredible discovery by CHIME/FRB and STARE2 of an FRB from a Galactictic magnetar, I have started to consider alternative FRB engines, in particular accretion-powered jets from stellar-mass compact objects and binary neutron star mergers (work spearheaded by my student Navin Sridhar). While I still believe magnetars are likely (perhaps the most likely) FRB sources, their “stock” now feels a bit overvalued relative to the probability of them being the sole central engine, given new observational hints and the generic nature of the mechanisms (“shocks”, ”reconnection”, ”wave decay”) likely responsible for generating FRB emission.

I have also done work on FRB emission theory, in collaboration with Lorenzo Sironi and Ben Margalit, on further developing the magnetized shock (“synchrotron maser”) mechanism. One of our contributions was to show that a decelerating blastwave (from an arbitrary injection of relativistic energy) which propagates into an external magnetized environment would naturally generate downward drifting frequency structure in the burst as well as an [incoherent] gamma-ray/X-ray synchrotron afterglow in the downstream region of the shock, from the same electron population responsible for the FRB. Incidentally, our predictions for the luminosity and spectrum of this X-ray emission nicely matched that which accompanied FRB 200428 from SGR 1935+2154, when rescaled to the lower energy of this event.

Proposed Talk: X-ray Binary Jets as FRB Sources

I will advance the hypothesis that some FRBs are powered by flares that occur in the evacuated accretion funnels of accreting stellar-mass black holes or neutron stars. Although I could (and we have) delved into possible emission mechanisms of coherent radio emission, my main argument is by a simple analogy: the most developed theoretical models for FRB prompt emission in magnetar magnetosphere or outflows (e.g., relativistic magnetized shocks, magnetic reconnection in a striped magnetar wind, non-linear wave decay) could equally occur in the magnetospheres or outflows of X-ray binary jet. For example, recent GRMHD and particle-in-cell plasma simulations of black hole accretion flows, have uncovered the creation and ejection of plasmoids along the evacuated funnel (the analog of magnetar flares), while there are theoretical reasons to believe accretion-powered jets may possess a radially-alternating magnetic field orientation (the analog of striped pulsar winds). Of course, this does not imply that all X-ray binary jets are necessarily FRB sources: special conditions, such as a particularly powerful jet, or one threaded by a sufficiently high magnetic flux, may be required to produce sufficiently luminous radio emission to detect at large distances, or for the FRB to escape the viscinity of the source without attenuation.

If one accepts X-ray binary jets as putative FRB sources, then a number of consequences follow. For example, periodic arrival windows of the burst (such as the 16 day period observed

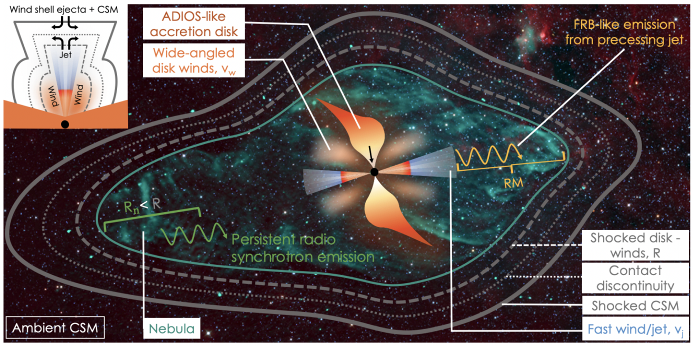

Figure 1: Schematic diagram of the disk wind/jet-inflated nebula. The central black hole or neutron star accretes matter at near or exceeding super-Eddington rate from a companion star undergoing thermal- or dynamical timescale mass transfer. The radiatively inefficient accretion disk is subject to strong outflows in the form of wide-angled disk winds, which feed mass and energy into the large-scale environment, and helps shape the polar accretion funnel and the jet cavity. The wind-fed ejecta shell drives a forward shock (solid grey curve) into the ambient circum-stellar medium (CSM, of density $\rho_{\rm csm}$) that is separated from the ejected shell/shocked disk-jet winds (dashed grey curve; at a distance R given by Eq. 10) by a contact discontinuity (dotted grey curve). The top-left inset shows how the jet 'head' and the disk winds feed matter into their environment and shape-up their surroundings. Yellow wiggles emanating from the jet cavity represents an FRB-like coherent radio pulse beamed along the instantaneous jet axis. The radio pulse travels through a nebula of electrons (green cloud) gyrating around the local magnetic field that imparts a large rotation measure (RM) to the pulse; the electrons cool via various radiative and expansion losses, generating persistent synchrotron radio emission. These electrons are energized and injected into the nebula by the shock formed at the jet - CSM/wind- shell interface. The location of this termination shock determines the boundary of the nebula (with a 'size' R_n). The asymmetric/bipolar shape of the nebula is the result of the higher ram pressure of the jet/disk outflows along the polar accretion axis (with velocities $v_j \gg v_w$) and within the precession cone of the jet (possibly responsible for imparting periodicity in the active FRB phase). The filamentary green structure underlying the schematic is an image of the W50 ('Manatee') nebula surrounding the ULX-like microquasar SS 433.

in FRB 180916) can naturally arise, since - due to relativistic beaming facilitated by geometric beaming - only viewers looking down the barrel of the jet at any given time will observe an FRB. The jets of ultra-luminous X-ray sources are well known to exhibit precession, potentially driven by a number of effects, most notably Lens-Thirring torques, when there exists a misalignment of the disk's angular momentum with respect to the black hole spin. An association between FRB and star-forming galaxies is also expected in luminous X-ray binary models, insofar that both ULX and FRB appear to exhibit a preference for star-forming galaxies (though with spatial offsets between the locations of the most active star-formation, as seen clearly for the ULX population in the Antennae).

A key lesson from the luminous persistent radio emission, and high and time-variable rotation measures, which accompany the environments of several repeating FRBs, is that these FRB sources are embedded in a dense *electron-ion* medium (which basic energetic arguments suggest may be powered by the same activity giving rise to FRBs). While it is uncertain whether pulsar or magnetar outflows contains a substantial ion component, large electron-ion nebulae are directly observed surrounding luminous X-ray binaries, powered by the baryon-rich disk winds which accompany radiatively-inefficient super-Eddington accretion. A famous example is the W50 ("Manatee") nebula surrounding SS433, though the nebula which accompany the most energetic FRB sources may be even more powerful (so-called "ULX Hyper-nebulae"). As I will show, the observed synchrotron properties and high RM values inferred for the persistent source of FRB 121102 are reproduced by a simple model for synchrotron-emitting ULX hyper-nebulae, assuming the progenitor binary to a young ($\lesssim$ decades old) source with an exceptionally high accretion rate $\dot{M} > 10^5 \dot{M}_{\rm Edd}$. These requirements are similar to those which are predicted to immediately precede common envelope events involving a massive star overflowing its Roche Lobe onto a neutron star or black hole companion. A cessation of activity from repeating FRB sources may then be accompanied by a luminous optical/X-ray transient from the common envelope inspiral - at the very least a luminous red nova or dusty infrared transient, or more speculatively a fast luminous optical transient.

Cornell FRB Workshop Biography and Summary: measuring RFI at potential GReX cluster sites

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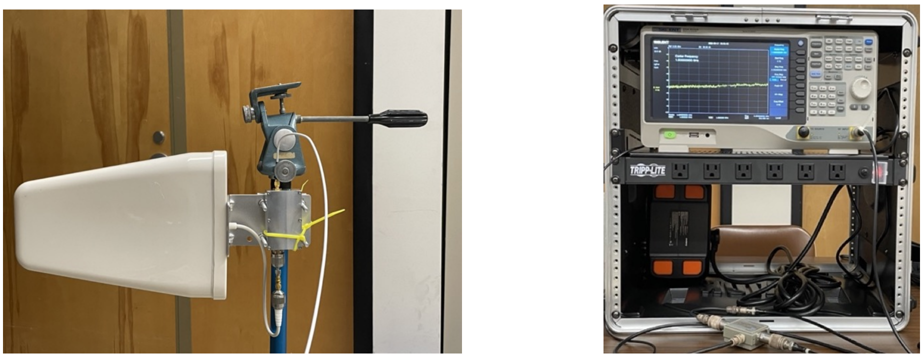
Summary

We are working with Liam Connor on the Galactic Radio Explorer (GReX) telescope. The GReX project seeks to install an international all-sky monitor to study the galaxy in the 0.7-2.0 GHz range [Connor et al., 2021]. As a real-time telescope, GReX will detect sources with $\sim 10\ \mu$s time resolution and save pertinent data for comparison with other clusters in the network. The spread of clusters will work to lower the effect of local RFI and provide a global baseline for the telescope. The antenna design is based on the STARE2 pancake antenna and will use the same LNA as the DSA-110. Target sources are galactic FRBs and giant pulsar pulses, with the additional hope of discovering new phenomena.

Cornell University will host one of the GReX antenna clusters. James Cordes, Shami Chatterjee, and I have constructed a portable device for exploring the levels of RFI present at different possible antenna sites. The device is housed within a standard Gator rack for portability that contains a Siglent Spectrum Alanyzer (SSA) 3032X. The rack also houses a bias-T and bandpass filter, along with the power supplies required to run the SSA and supply the bias-T (Figure 1b). The SSA is connected to a Wideband Directional Antenna from Wilson Electronics that is attached to a portable tripod. The DSA-110 LNA is attached directly to the output of the antenna (Figure 1a).



(a) Antenna & LNA.

(b) Gator rack.

Figure 1: Left: the Wideband Directional Antenna from Wilson Electronics and DSA-110 LNA attached to a portable tripod. Right: the Gator rack holding the SSA (top) and power supply (bottom) with bias-T (unattached).

I have written a python script based on the code written by Kiran. Kiran's code is a publically available modern python library for interacting with

Siglent-brand test equipment on github. My script communicates with the SSA, allowing for control of the device from a computer attached by USB or Ethernet. The script also extracts data from the SSA at a user-defined rate greater than 10s, and saves the data in .npy format. We use this script to save hour's worth of RFI data for later examination to get a full understanding of RFI pervasiveness at each potential cluster site.

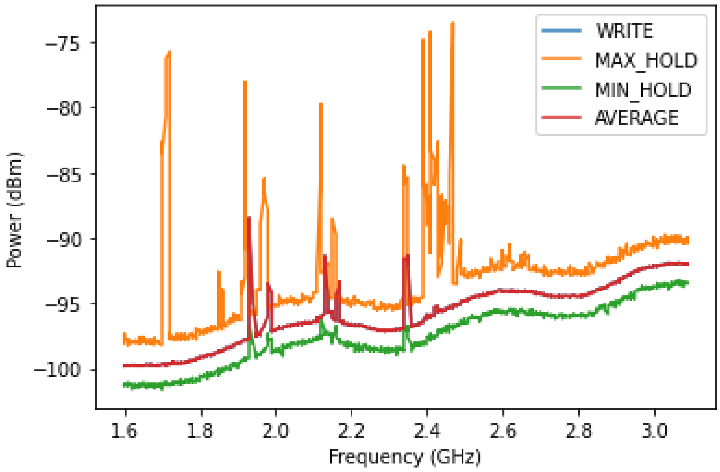


Figure 2: Plot of the data extracted from the SSA using my script. This is one of multiple plots collected. It is possible to construct a video time lapse of RFI using this data to inspect the intensity changes over time.

Biography

My name is Sashabaw Niedbalski and I am a graduate student in the Cornell University Astronomy department. I graduated from Hillsdale College in 2021 with degrees in mathematics and physics. While at Hillsdale, I worked with Timothy Dolch in constructing the Low-Frequency All-Sky Monitor (LoFASM) V station. I also wrote python scripts for analyzing the data gathered by LoFASM V. I also worked with David Neilsen of BYU on simulating binary BH mergers using the Post-Newtonian approximation. At Cornell, I am working as a research assistant with James Cordes on a number of different radio astronomy projects. My main interests are FRB detection, machine learning, and pulsar astronomy. My current projects are in exploring the use of machine learning as a method of real-time FRB detection and the GReX project.

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KENZIE NIMMO

I am a Kavli fellow at MIT. I recently completed my PhD at ASTRON (Netherlands Institute for Radio Astronomy) and the University of Amsterdam as part of the AstroFlash team (led by Jason Hessels). My PhD thesis is titled "Zooming-in on the sources of fast radio transients" and is primarily focused on studying fast radio bursts (FRBs) at the highest possible time (down to tens of nanoseconds) [1, 2, 3] and spatial (down to milliarcsecond) [4, 5, 6] resolutions. We use both single-dish Effelsberg observations running in "baseband" mode to record the raw voltages, as well as global very-long-baseline interferometric (VLBI) observations using the European VLBI Network (EVN). This work has provided insights into both the emission mechanism and progenitor of FRBs. As a postdoctoral fellow, I have joined the CHIME/FRB collaboration to scale up this work using the CHIME Outrigger project and already existing large CHIME FRB sample.

BRIDGING THE GAP BETWEEN GALACTIC NEUTRON STARS AND FRBS

Despite over a decade of research [7], the nature of FRB emission remains an incredibly exciting open problem in modern astrophysics. FRBs are more than 10 orders of magnitude brighter compared with emission typically seen from Galactic neutron stars on comparable timescales. FRBs therefore represent an extreme physical process. Could more extreme neutron stars (perhaps in their magnetic field strengths or spin periods; e.g. [8]) be responsible for this jump in luminosity or are FRBs coming from other astrophysical objects/systems?

Nearby sources of FRBs are incredibly valuable for bridging the gap in knowledge from Galactic sources of short-duration radio transients to the much more distant FRBs. One example is the Galactic magnetar SGR 1935+2154, which produced an FRB-like radio burst detected by both the CHIME/FRB [9] and STARE2 telescopes [10]. This shows that at least some FRBs must come from highly magnetised neutron stars in other galaxies. Despite being many orders of magnitude brighter than other fast radio transients previously seen from magnetars, this event was still 1—2 orders of magnitude weaker than extragalactic FRBs, hence the term "FRB-like" as opposed to simply "FRB". Until recently, there still remained a huge jump from a known magnetar at a distance of 9 kpc [11] to the nearest FRB source FRB 20180916B at 149 Mpc [5].

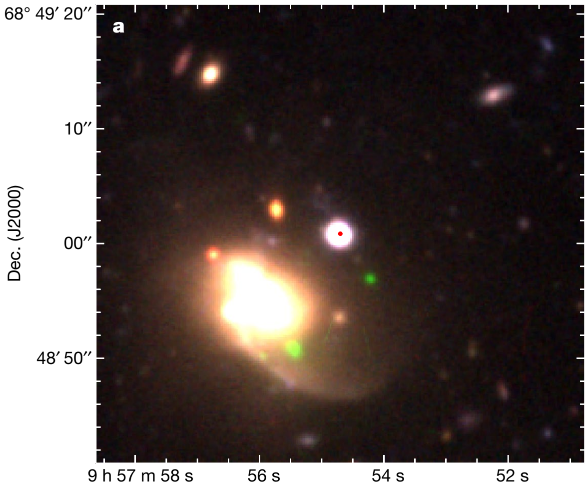

Figure 1: The PRECISE localisation of FRB 20200120E to a globular cluster in the M81 galactic system. Optical image of the host obtained using Hyper Suprime-Cam, with the FRB position shown by the red marker [6].

More recently, the CHIME/FRB team discovered a repeating FRB (FRB 20200120E) coming from the direction of the grand-design spiral galaxy M81 [12], which is at a distance of *only* 3.6 Mpc. Using an ad-hoc array of radio telescopes (project PRECISE; PI Franz Kirsten), we precisely localised this repeating FRB to a globular cluster in the M81 galactic system (Figure 1) [6]. Not only did this confirm the FRB's association with M81, but the globular cluster origin is in stark contrast to other well-localised repeating FRBs, which live in close proximity to star formation (e.g. [13, 14]). This sparks the question: does FRB 20200120E have the same type of progenitor as other repeating FRBs? If it is a magnetar, it was not created through the typical core-collapse of a massive star but perhaps through the merger of compact objects or accretion-induced collapse of a white dwarf.

Using the 100-m Effelsberg telescope, we have been monitoring FRB 20200120E to study the distribution of burst properties and temporal evolution of the source, to compare with similar studies of repeating FRBs. We find that, observationally, FRB 20200120E shares a number of properties with other repeating FRBs including: burst clustering in time, with rates varying per observing epoch; a bimodal wait time distribution; a variety of burst morphologies; and distinctive polarimetric properties (high linear, no circular and flat polarisation angles) [2, 3]. In addition to the globular cluster origin, however, there are notable differences: the bursts are at least 100 times less luminous and 30 times shorter in duration than other repeating FRBs.

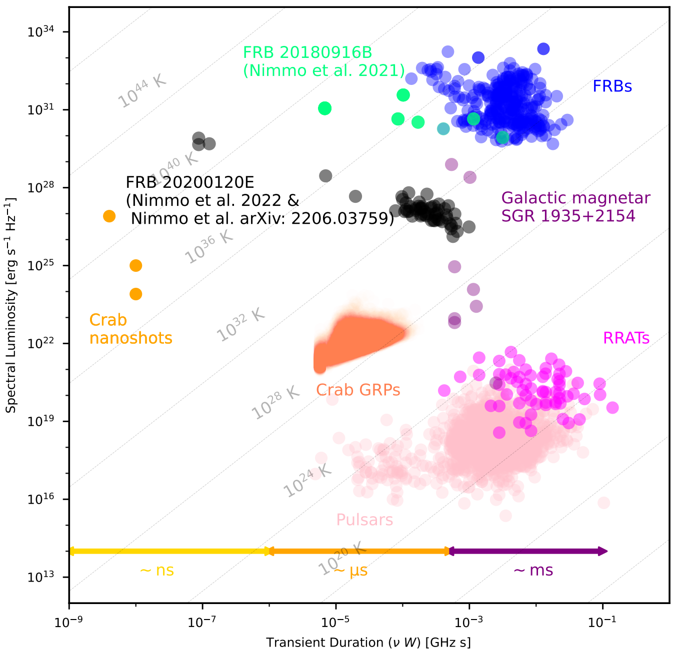

Figure 2: The transient phase space of short-duration radio transients. Adapted from [2] for my PhD thesis.

The FRB 20200120E luminosities are weaker than SGR 1935+2154's "FRB-like" event (Figure 2), further strengthening the connection between extragalactic FRBs and magnetars. Additionally, we probe timescales down to 30 ns, showing a *spectrum* of short-duration radio transients spanning many orders of magnitude in both timescales and luminosity (Figure 2). These shortest timescales, however, are somewhat rare, with only one burst exhibiting sub-µs structure out of 65 bursts.

It will be interesting to explore whether FRB 20200120E can produce even brighter bursts, more comparable to other repeating FRBs through continued monitoring (although our current observations of the energy distribution does not suggest this). Similar studies of other nearby repeating FRBs ($<$ 100 Mpc), and conducting FRB searches in Milky Way globular clusters, may help to populate the "middle" luminosity gap of the transient phase space, where current radio telescopes cannot reach for the extremely distant FRBs.

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Implications of the Scattering Budget for Fast Radio Burst Sources and Applications

Name: Stella Koch Ocker **Email**: sko36@cornell.edu

Bio: I am a PhD Candidate working with Jim Cordes and Shami Chatterjee at Cornell. My dissertation focuses primarily on radio observations of plasma extending from the very local interstellar medium (ISM) to the extragalactic source environments of FRBs, and subsequent applications to the study of extreme astrophysical phenomena including compact objects, gravitational waves, and circum/inter-galactic media (CGM/IGM). I am a NASA Outer Heliosphere Guest Investigator on the *Voyager Interstellar Mission*, where I have led the detection of persistent plasma wave emission, enabling continuous electron density measurements in the very local ISM. I am also a Full Member of the NANOGrav Collaboration, where I apply the study of pulsar dispersion and scattering in the Galactic ISM to the astrophysical noise budget for gravitational wave detection with pulsar timing. My work on FRBs spans the use of propagation effects to probe their local environments and host galaxies, to constraints on the distribution and turbulence of plasma in the CGM of the Milky Way and other galaxies. A list of my publications can be found at this stellakochocker.com.

Talk Summary: Scattering plays a critical role in FRB propagation, detection, and subsequent use as astrophysical probes. FRB lines-of-sight (LOSs) are typically divided into a few main components: the Milky Way (ISM and CGM), the IGM, intervening galaxies, and host galaxies (CGM, ISM, and circumsource medium or CSM). Unlike dispersion, scattering is observable as a range of time and frequency-dependent effects (pulse broadening, scintillation, angular broadening), which can be combined to constrain the location(s) of the scattering medium(s) and hence the scattering budget. This method has been applied to localized FRBs and demonstrated that not only is their scattering dominated by their host galaxies and the Milky Way ISM, but also that scattering in the CGM and IGM appears to be negligible (Ocker et al. 2021a, Cordes et al. 2022b). This result alone has a few key implications:

- Detection of scattering from within host galaxies constrains the degree of density fluctuations therein, which provides a metric for comparing the properties of ionized gas in FRB hosts and the Milky Way. The relative scattering contributions of host ISM vs. FRB local environment remains ambiguous in many cases, although scattering time variations have recently been detected from the CSM of one repeating FRB (Ocker et al., under review).
- Scattering from host galaxies can be used to improve the precision of the DM budget and redshift estimation of non-localized sources (Cordes et al. 2022b, Ocker et al. 2022a).
- Multi-phase models of the CGM must reconcile empirical upper limits on FRB scattering through the CGM of the Milky Way and nearby halos with the proposed prevalence and size scales of “cool” (~10^4 K) cloudlets in CGM gas.

Scattering is also an important selection effect in FRB surveys and biases the observed FRB population — based on CHIME/FRB Catalog 1, a significant fraction of FRBs appear to be unobserved by CHIME due to scattering (CHIME/FRB Collaboration 2021, Chawla et al. 2022).

So where and how do these undetected FRBs incur large scattering? The exact amount of scattering from a given medium depends on its inclination relative to the LOS, its electron density distribution, its redshift (and that of the source), and the observing frequency. Generally speaking, host galaxies and the Milky Way may dominate FRB scattering out to redshifts ~1, but as source redshifts increase the amount of scattering from host galaxies is dampened by time dilation, while the number of intervening galaxies increases substantially enough to begin contributing significantly to the total LOS scattering. As such, a significant fraction of high-redshift ($z > 1$) FRBs may be unobserved due to scattering alone, particularly below 1 GHz (Ocker et al. 2022b).

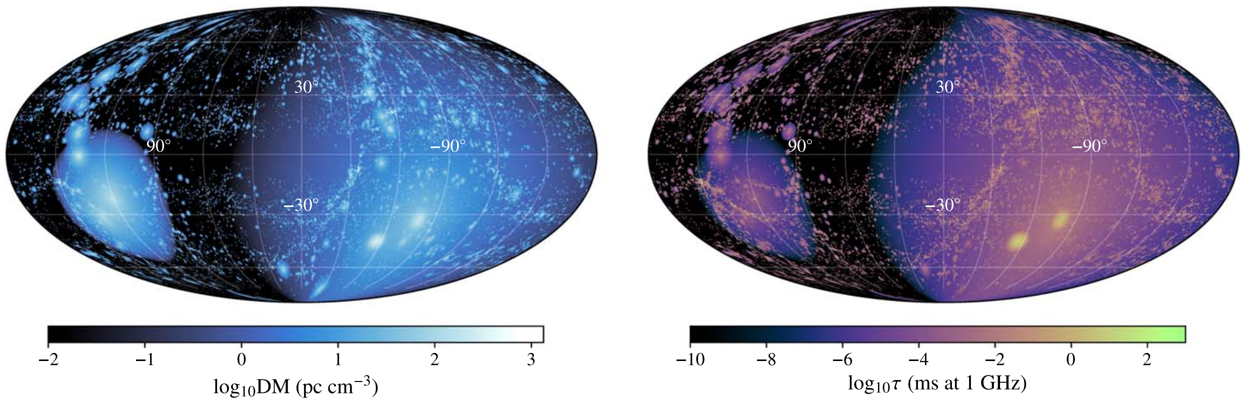

Figure 1. All-sky maps of the predicted DM (left) and scattering time at 1 GHz (right) contributions from galaxies within 100 Mpc, for FRB source redshifts > 0.1. The angular extents of the galaxies' halos were estimated using twice the virial radii and their distances (taken from the Gravitational Wave Galaxy Catalog). Figure from Ocker et al. (2022b).

Given that host galaxies appear to play an important role in FRB scattering for the observed population (largely $z < 1$), studies that aim to constrain FRB progenitor models based on, e.g., their host galaxy properties and source locations need to contend with how scattering (or lack thereof) affects burst detection. If local environments can contribute variable scattering, then the interpretation of scattering from apparent one-off events becomes more ambiguous: the scattering of one burst may not be representative of the local environment as a whole.

Regardless of the degree to which FRBs are unobserved due to scattering, those that are observed enable a number of interesting scattering applications. At low redshift, these applications include:

- FRB DMs, scattering times, and rotation measures can be combined with angular broadening observations of active galactic nuclei (AGNs) to constrain the distribution and turbulent magnetic fields of the CGM in the Local Group. There are now several FRBs and AGNs viewed through the halos of M31 and M33, and there are expected to be many more FRBs detected through these halos in the near future given their large angular extents on the sky.
- Similarly, the Magellanic Clouds cover large angular extents on the sky, and their plasma density distributions remain poorly constrained by their sparsely observed pulsar populations. FRBs detected near and through the Magellanic Clouds will constrain their density distributions and also probe gas bridges and interactions between the Milky Way and these satellite galaxies.
- Very low DM FRBs (i.e., those which do not appear to be extragalactic based on NE2001, YMW16, and/or models of the Milky Way halo) will test the accuracy of Galactic electron density models for the ISM and CGM and serve as input to the next generation of these models. These FRBs (combined with Galactic pulsars) are also the first empirical "rungs" on the FRB DM-distance ladder. With a large enough localized sample, one can imagine a future version of the FRB DM budget that is based on statistical analysis of FRBs across a wide range of DMs and redshifts, as opposed to a highly model-dependent DM budget. Analyses along these lines will ensure that the large, non-localized sample of FRBs does not get left by the wayside after the advent of localization machines like DSA-110/2000 and CHIME outriggers.

I expect that 20 minutes is not sufficient time to cover all of the topics raised in this summary. I am happy to focus on a subset of these topics based on feedback from the conference organizers and session chairs.

References: (1) Ocker, Cordes, & Chatterjee. *ApJ* 911:2. doi:10.3847/1538-4357/abeb6e (2021). (2) Cordes, Ocker, & Chatterjee. *ApJ* 931:88. https://doi.org/10.3847/1538-4357/ac6873 (2022). (3) Ocker, Cordes, Chatterjee et al. *ApJ* 931:87. https://doi.org/10.3847/1538-4357/ac6504 (2022). (4) CHIME/FRB Collaboration. *ApJS* 257:59. doi:10.3847/1538-4365/ac33ab (2021). (5) Chawla et al. *ApJ* 927:35. doi:10.3847/1538-4357/ac49e1 (2022). (6) Ocker, Cordes, Chatterjee, & Gorsuch. *ApJ* 934:71. https://doi.org/10.3847/1538-4357/ac75ba (2022).

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Surveying the nearest FRBs

U-L. Pen^{ASIAA,CITA*}

13 September 2022

1 SELF-INTRODUCTION

I am Ue-Li Pen, currently director of the Academia Sinica Institute for Astronomy and Astrophysics in Taiwan, and on part time leave from the Canadian Institute for Theoretical Astrophysics. My background is in theoretical cosmology, which lead to interests in 21cm cosmology and dedicated experiments. I instigated the CHIME experiment in Canada following an initial prototype with Jeff Peterson in Pittburgh. After assembling the CHIME cosmology team in Canada, we expanded the novel fast survey instrument team to include an FRB back-end and science team. The large field of view delivered a high FRB discovery rate, but filled aperture had limited localization capability. Expanding on previous pulsar VLBI experience, we deployed VLBI FRB outrigger pathfinders at Algonquin (Ontario) and Green Bank (TONE), resulting in the field VLBI localization of non-repeating FRBs. The Moore foundation invested in 3 cylinder outriggers that aim to localize all CHIME FRBs.

While CHIME was optimized as a 21cm instrument, the next opportunity is a dedicated FRB instrument that surveys the whole sky all the time with VLBI outriggers. The Taiwan BURSTT initiative aims to fill this niche.

2 BURSTT

The quest for multi-wavelength and multi-messenger counterparts is limited by the instantaneous field of view of FRB surveys. CHIME, being the largest, only monitors less than one percent of the sky. An effort to monitor the whole sky maximizes the possibility of catching an FRB at the same time as another band, including high energy, gravitational waves, neutrinos or cosmic rays. Catching the nearest FRBs as they burst will also fill the bridge to local counterparts in the milky way or neighboring galaxies.

The BURSTT telescope is a phased array imager, in close design analogy with CHIME, but without the cylinders (arXiv:2206.08983). It forms all sky beams all the time, in analogy to an FFT telescope (Tegmark and Zaldarriaga 2009, PRD 79, 083530). The sensitivity and Field of View comparison are shown in Figure **??**.

Its first phase, currently under deployment, consists of a main station with 256 elements in Fushan, with 3 outrigger stations across Taiwan and outlying islands, as well as a station in Hawaii. The main station is illustrated in Figure **??**

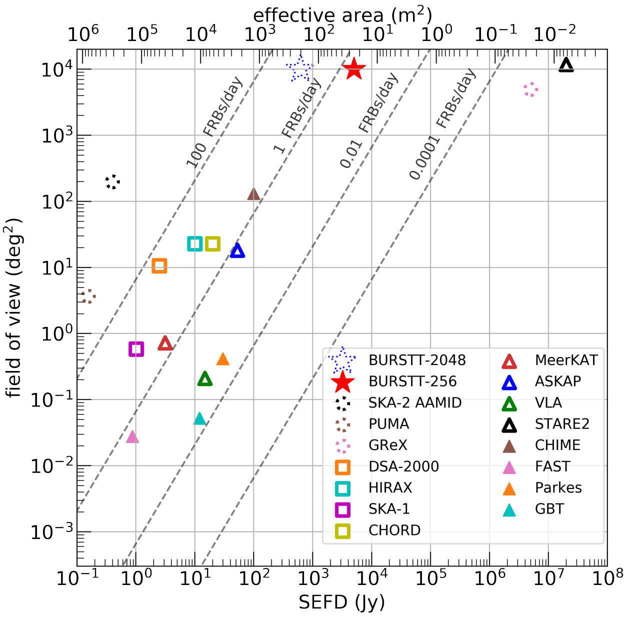


Figure 1. Comparison of BURSTTs FoV, effective collecting area, sensitivity (SEFD), and FRB detection rate (dashed lines) vs. existing (solid), planned (outline), and future-concept (dotted circle) observatories. Rates(dashed lines) were calibrated to CHIME, assuming Euclidean rates and 400 MHz bandwidth. Open triangles are sparse interferometers, which provide arcsecond localization and would require correlator upgrades to achieve these rates. The rate is a hypothetically upper limit, with the assumption of 24/7 FRB searches (which only CHIME/FRB does) as well as the optimal FRB searches with coherently beam-forming for the interferometry (ASKAP, VLA). BURSTT is unique in the large FoV with enough sensitivity to detect a large sample of bright and nearby FRBs.

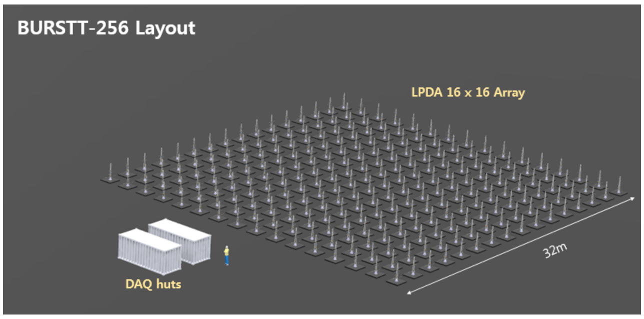


Figure 2. BURSTT 256-antenna array station layout.

3 FUTURE

The FFTT design is linearly scalable, with the next stage goal a 2048 element main array. The FRB rate is proportional to $n^{3/2}$, where n is the number of elements, so the cost per FRB decreases with increasing antenna count. The dominant cost in the current system lies in the RFSoC digitizing FPGA. The development boards cost approximately \$1000/antenna.

The intrinsic cost of digitization can be substantially lower, and our group has been experimenting with commodity USB controllers such as the Cypress EZ-USB, potentially making an order of magnitude cost reduction feasible. Arrays with $O(10^5)$ elements, detecting thousands of FRBs per day could be implemented. We encourage the community to explore science with very large samples.

This paper has been typeset from a TEX/LATEX file prepared by the author.

Sterl Phinney
Professor of Theoretical Astrophysics at Caltech

I am a theoretical astrophysicist, who has worked on many different topics. These include theory of accretion disks, black hole energy extraction, jet propagation, evolution of single and binary pulsars in the Milky Way and in globular clusters, neutron star mergers, stellar evolution and stellar tides, quasars, the ionization of clouds in the intergalactic medium, tidal disruption of stars by black holes, and the propagation of FRB signals. I have also had leadership roles in the science teams of various space missions, including LISA, Ultrasat and currently UVEX.

In the FRB field, I am most interested in the use of FRBs to probe the circumgalactic medium of intervening galaxies, and to measure their near-host environments, respectively through the use of plasma lensing and strong-wave effects. I would love to understand the nature of FRB sources' structure and emission mechanisms, but having worked on pulsars for nearly 50 years, am less optimistic about definitive results in that area.

New repeating sources of FRBs from CHIME/FRB

Ziggy Pleunis (ziggy.pleunis at dunlap.utoronto.ca)

Dunlap Fellow at the Dunlap Institute for Astronomy & Astrophysics, University of Toronto

Talk summary

The CHIME/FRB project has so far discovered twenty sources of repeating FRBs, which has directly and through targeted follow-up observations led to many advances in our understanding of FRBs. We present an updated sample of repeating sources of FRBs discovered from late 2019 to mid 2021. In order to uniformly search our events for repeating sources, we employed a clustering algorithm on all events in our database. The 25 new repeaters identified this way more than double the number of known repeaters (see Figure), providing new targets to follow up and a much larger sample for comparisons with apparent non-repeaters. I will present the new sources, our repeater detection rate over time and updated population comparisons. Based on these and previous results I will argue that not all FRBs repeat and that there are multiple populations of FRBs.

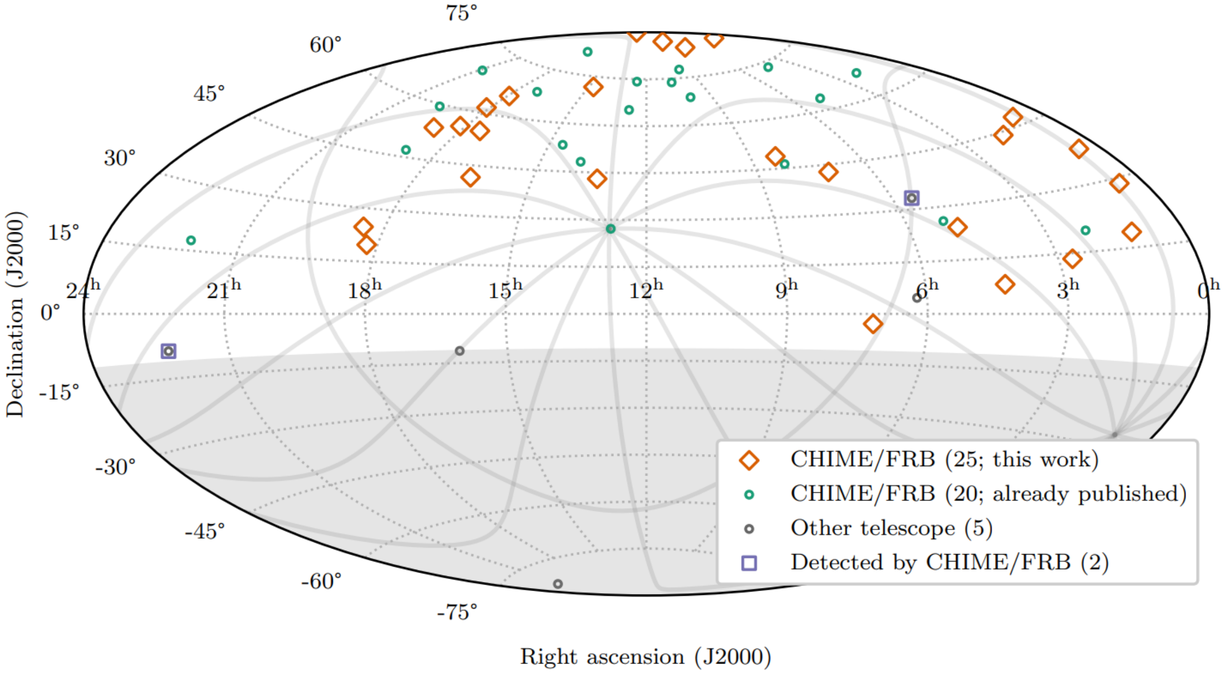


Figure: *Sky distribution (Aitoff projection) of repeating sources of FRBs discovered by CHIME/FRB (orange open diamonds and green open circles), discovered by other telescopes (gray open circles) and detected by CHIME/FRB. Declination < -11 degrees is outside of CHIME/FRB's field-of-view and colored gray. The gray solid lines in the background show the plane of the Galaxy (b = 0 degrees) as well as lines of constant Galactic longitude 0 to 360 degrees in steps of 30 degrees.*

Self-introduction

Hi, my name is Ziggy Pleunis and I am currently a Dunlap Fellow at the University of Toronto's Dunlap Institute for Astronomy & Astrophysics, where I collaborate mostly with Bryan Gaensler's and Keith Vanderlinde's research groups. I am a member of the CHIME/FRB Collaboration and I have recently been working on identifying and interpreting new repeaters in CHIME/FRB data and commissioning the Outriggers upgrade to the experiment. I have also been working towards a better understanding of the magnetized environments of FRBs and I have been using the LOFAR telescope to detect the lowest-frequency FRBs. Before moving to Toronto I obtained a PhD in 2020 at McGill University under supervision of Vicky Kaspi and a master's in 2016 at the University of Amsterdam under supervision of Jason Hessels. In my free time I like to read, listen to music and cook.

A Software Strategy for Flexibility and Reliability

Kiran Shila

September 13, 2022

1 Author Biography

Kiran Shila is a Ph.D. in Electrical Engineering at Caltech, under Sandy Weinreb's and Gregg Hallinan's supervision. His educational background includes RF circuit design, phased array and mm-wave antennas, and computer engineering. Kiran graduated with B.S. and M.S. degrees in electrical engineering from the University of South Florida in Tampa, where he received the King O'Neal Award, Outstanding EE Graduate, and the Rudy Henning Award for Excellence in Microwave Studies. Before Caltech, Kiran worked at the NASA Goddard Spaceflight Center on mm-wave radiometer systems for earth science missions and the MITRE Corporation on beyond-line-of-sight communication systems.

Outside of studies, Kiran enjoys playing percussion with the Caltech Jazz Improv group and the Caltech Wind and Symphonic Orchestras. You will also find Kiran biking around the hills in Pasadena or at home, contributing to open-source software.

2 Abstract

The Galactic Radio Explorer (GReX) Telescope is fundamentally a software instrument. The capability to detect radio transients at such high resolution is not due to novel analog hardware or FPGA code but rather due to the implementation of a streamlined data collection and processing pipeline. Additionally, GReX is unique in that we plan to deploy stations worldwide, requiring substantial forethought in software design and deployment. Instead of the "traditional strategy" of throwing together scripts and collections of virtual environments, GReX utilizes a fully deterministic build and deployment system coupled with formatted, documented, and linted code. We strategized this to maximize uptime, allow easy customization and configuration, and quickly onboard those who want to contribute to the code base.

This talk will consist of two parts. First, we will discuss the role of the Guix package manager in the GReX system. Guix is GNU's deterministic build system in which we create package definitions that fully describe the entire dependency graph of a given application or library. Once defined, one can recreate these packages bit-for-bit. In the context of GReX, we package all pipeline software, associated scripts, and transitive dependencies in Guix. We also package the server software within Guix, where the kernel, networking configuration, etc., is just another package. This strategy allows us to have minimal configuration files and collect the full description of the software system into a single source of reproducible truth.

The second portion of the talk will cover the decision to use the Rust programming language for large chunks of the software. The Rust language is a modern systems language designed for correctness. As the GReX systems will be primarily remote, we want to develop software with compile-time guarantees of certain classes of runtime behavior. In addition, we want confidence that once compiled, our software will not crash or, at the very least, does so in a predictable manner. We will discuss the language features in Rust that make this possible and how the current software fits into the greater pipeline context.

To understand FRB emission mechanisms better and to specifically identify the astrophysical objects that produce FRBs, we need to focus on the nearest and brightest FRBs which are the ones most likely to produce detectable multi-wavelength and multi-messenger counterparts (X-/γ-rays, GW, neutrinos). I will discuss our efforts from the point of view of two main FRB origins — magnetar flares (along the lines seen from SGR 1935+2154) and compact binary coalescences (CBCs) with at least one neutron star.

Radio Counterparts to CBCs

There exists an observational gap in the transient phase space that is largely unexplored from about 0.1 s to a few minutes. Pulsars and FRBs are exquisitely studied at timescales shorter than about 50 ms and TDEs, GRB afterglows and SNe shocks are studied at hour to year timescales. By leveraging the very high survey speed of the CHIME/FRB telescope, it's multi-beam design, and stability, we propose to do the first systematic survey of the transient radio sky at timescales between 50 ms to 5 s. This is particularly relevant from the point of view of prompt radio counterparts of CBCs involving neutron stars since while a prompt radio counterpart is widely expected, the timescales at which these bursts might emerge and their properties are very poorly understood. With the CHIME/Slow Transient Search (CHIME/STS), we (mainly S. Mate, K. Luke @TIFR, Z. Pleunis, P. & Scholz @UoT) are starting a search of CHIME data at these timescales. Apart from CBC mergers, this survey will be sensitive to extremely scattered FRBs, long period magnetars, white dwarf and M-dwarf flares. We expect to do a pilot offline search by the end of 2022 and expand to a larger scale system (funded by Dunlap Institute) next year subject to resource availability.

Brightest FRBs

The need for detecting and localizing ultra-bright FRBs is well-understood. We are working on designing and building an All-Sky Transient Radio Array (ASTRA), a 400–800 MHz open dipole array with a specially designed feed (Figure 1, left panel) with a 3dB field of view (FoV) of $120° \times 130°$. ASTRA will have 700 dual-polarized signal chains, and most importantly, a $\approx$300 s voltage ring buffer on most (if not all) signal chains designed to respond to internal as well as external (e.g. ASKAP, OWFA, LIGO) triggers. There will be three stations separated by $\approx$ 30 km to provide an arcsecond to subarcsecond localization, sufficient for host and counterpart identification for nearby FRBs. The expected rate of FRB detection with such a system would be about 1 per two-three weeks with a sensitivity threshold of 700 Jy ms.

The current vision is to place these stations along empty GMRT pads which already have power and fiber optic lines running to them. However, Ooty Radio Telescope and Gauribidanur Radio Observatory (each with an existing maser clock and offering baselines of 200–900 km) have been identified as potential alternatives or expansion sites.

At TIFR in collaboration with RRI, we have designed (and are now testing) the ultra-wide FoV antenna (Figure 1, left panel). Though the antenna is designed to operate between 400–800 MHz, the digital systems initially would use only digitize 100 MHz of the band. The digital systems are being designed at TIFR and NCRA. We expect to set up a pilot system with 16 signal chains in Spring 2023 at the GMRT site.

Multiwavelength Counterparts — *Daksha*

The detection horizons of transient X-ray and γ-ray telescopes are significantly sensitivity limited. *Daksha* (Figure 1, right panel) is a multi-institution proposed space mission with an all-sky coverage from 1 keV to > 1 MeV at a fluence threshold of $4 \times 10^{-8}\,\mathrm{erg\,cm}^2$ using 2 satellites in anti-podal orbits. *Daksha* consists of three separate high technological readiness level detector

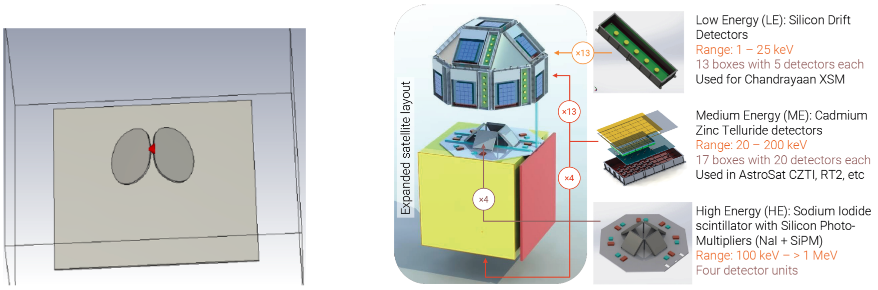


Figure 1: *Left Panel:* A 400-800 MHz ultra-wide FoV feed designed for ASTRA. The design is based on the CHIME feed, but is adapted for wider FoV and simplified for transient detection. *Right Panel:* An exploded view of one of the two *Daksha* satellites showing the three detector systems — low energy silicon drift detectors, medium energy CdZnTe detectors, and high energy NaI scintillators.

systems that have demonstrated space heritage. The effective area of the 20–200 keV CdZnTe detectors is 1300 sq. cm. (all-sky median, single satellite) is equivalent to that of Swift-BAT but with $\sim 10\times$ larger FoV. Apart from saving all received photons, *Daksha* will run optimized on-board transient detection issuing alerts with latency < 1 min.

Daksha will allow us to detect up to $\sim$10 EM counterparts of CBCs and $\sim$ 700 GRBs per year. It will be sensitive to magnetar giant flares (10^{47} erg) up to a distance of 140 Mpc. Fainter bursts, such as April 28 2020 burst from SGR 1935+2154 would be detectable within the entire Galaxy and its satellites. *Daksha* will be able to broadband prompt spectra of magnetar flares, microsecond timing, and Compton polarimetry above a fluence of $10^{-4}\,\mathrm{erg\,cm^{-2}}$. With improved sensitivity and higher detection rates, *Daksha* will provide a complementary view of FRBs allowing us to constrain both magnetar flare origins and binary neutron star merger origins.

Daksha has been given seed funding from the Indian Space Research Organisation, and laboratory models of the requisite systems are in a mature state of development. Once the development milestones are completed, *Daksha* will be reviewed for full mission approval.

Self Introduction — Shriharsh Tendulkar

I am a Reader (i.e. tenure track asst. professor) at the Tata Institute of Fundamental Research, Mumbai and at the National Centre for Radio Astrophysics, Pune in India. I am also a CIFAR Azrieli Global Scholar in the Gravity and Extreme Universe Program of the 2022-24 cohort. My academic arc goes like this: BTech Engineering Physics (IIT Bombay, 2008), MS Astrophysics (Caltech, 2010), PhD Astrophysics (Caltech, 2014).

My work focuses on magnetars, neutron stars, transients, and instrumentation (now in X-ray and radio) to detect and study transients. My PhD thesis (guided by SRK) was on using Keck adaptive optics to perform high-precision astrometry to conduct a kinematic survey of magnetars and to help design, build, and commission the RoboAO adaptive optics system on the Palomar 60-inch. I worked on understanding magnetar emission and accretion processes in transitional MSPs and ULXes (with newly discovered neutron stars) with NuSTAR. I then switched to radio astronomy helping design and build the CHIME/FRB and CHIME/Pulsar backends.

My group at TIFR and NCRA works on studying FRBs and X-ray transients. Apart from CHIME/FRB and CHIME Slow Pulsar Search, we are working on building the CHIME/FRB Slow Transient Search pipeline, the All Sky Transient Radio Array (ASTRA), and the Daksha X-ray mission.

Magnetars and Fast Radio Bursts

Christopher Thompson, CITA, University of Toronto

Bright, narrow radio bursts have been detected from a Galactic magnetar in outburst, but only limited progress has been made connecting this radio emission with the mechanism producing the much more luminous X-ray bursts. This talk will describe a simple mechanism relating the emission of 10-100 cm waves to a dynamic magnetic field that develops small-scale current structure. (Many more details can be found in the preprint arXiv:2209.11136.) Strong independent evidence for such structure during a magnetar outburst comes from the observation of quasi-thermal X-radiation. (High-wavenumber current perturbations mediate energy transfer between the magnetic field and embedded electrons and positrons.)

On occasion, the perturbed magnetic field may be ejected, forming a relativistically expanding pulse hundreds of kilometers wide. The small scale modes become frozen by the expansion; the focus is on their linear interaction with large-scale shocks. This couples the subluminal modes to a superluminal wave which can escape and be detected as a radio wave. In particular, a solution is found to linear perturbations of a relativistically magnetized shock wave. This generalizes the problem of an acoustic wave interacting with a shock to the richer array of modes present in magnetized plasma. Zero-frequency plasma modes colliding with the shock excite dynamic electromagnetic oscillations on the downstream side. This secondary emission is dominated by the ordinary wave – orthogonal in polarization to that produced by the shock maser instability. The amplitude of the reflected wave is negligible.

This mechanism has substantial advantages over the two main alternatives (the maser and reconnection-induced X-mode emission). First, in contrast with the maser, the process is efficient even if the upstream particles are relativistically warm and the shock is of moderate strength. Second, the formation of a turbulent spectrum of modes guarantees the presence of waves of size less than 10^{-6} of the outflow width but carrying $10^{-4} - 10^{-3}$ of the energy flux. Relativistic expansion stores energy in modes of wavelength in the radio range by limiting the cascade energy flux into particles.

My other recent work on magnetars and radio pulsars has been concerned with poorly understood physical processes, such as: How is a global yielding event with a duration of 0.1 seconds or longer triggered in a magnetar? The interactions of photons, electrons and positrons are radically altered in a super-QED magnetic field; how is a strong electric current and electromagnetic pulse excited and supported outside the star? What are the dominant instabilities to which this current is susceptible, and how is energy transferred from the magnetic field to charged particles and to radio waves? (See Thompson 2008, ApJ; Thompson, Yang and Ortiz 2017, ApJ; Kostenko and Thompson 2018, 2019, ApJ; Thompson and Kostenko 2020, ApJ; Thompson 2022a,b, ApJ.)

Other work connected with fast radio bursts has focused on the interconnection between gravitational lensing and plasma interaction of radio waves, exploring the radical (?) possibility that repeating fast radio bursts are emitted close to the event horizons of weakly accreting intermediate-mass black holes. A 2017 paper solved the problem of the 'Fast Radio Burst Green Function'. It was shown how a thin and subluminally expanding relativistic shell can linearly transform to a superluminal mode, and how the shell can 'upscatter' spatial structure in an ambient magnetic field into frequency structure in the bounced electromagnetic wave.

Yet earlier work investigated the origin of extreme magnetism in convecting and accreting proto-neutron stars. With R. Duncan, extreme magnetism in the remnant neutron star was connected with the phenomenon of repeating soft gamma-ray bursts and with a class of thermally emitting pulsating X-ray sources in the Milky Way. I also identified ultraluminous rotationally driven magnetized outflows as the source of the broader gamma-ray burst phenomenon, found a self-regulating mechanism localizing the dissipation in these outflows, with M. Russo explained how they accelerate, and with R. Gill worked out a constrained theory of gamma-ray emission based on simple properties of strongly magnetized pair plasmas. Novel aspects of QED processes operating in ultrastrong magnetic fields have been analyzed, mainly with A. Kostenko (photon splitting/merging, annihilation bremsstrahlung, etc) which explain key aspects of the X-ray spectra of bursting and quiescent magnetars. The decay of the magnetic field is driven by processes operating both inside and outside the star. With Kostenko I developed a simple solution to the external circuit and with Duncan, H. Yang and others have worked out the effects of temperature feedback on magnetic transport in the stellar interior, as well as a self-consistent global mode of yielding. Other related publications have focused on angular momentum transport and magnetic field growth in evolving stars.

About Dan Werthimer

Dan Werthimer is Chief Scientist of the Berkeley SETI Research Center and principal investigator of SETI@home and CASPER, the Center for Astronomy Signal Processing and Electronics Research. CASPER instrumentation made the first image of a black hole, and discovered a planet made from solid diamond and many pulsars and fast radio bursts. Dan has testified to congress about SETI, holds the Drake Award for SETI research and the Carl Sagan award for science education, and published 250 papers in the fields of SETI, astronomy, and science education; he is editor of "BioAstronomy: Molecules, Microbes and Extraterrestrial Life" and "Astronomical and Biochemical Origins and the Search for Life in the Universe. Dan has been associate professor in the engineering and physics departments of San Francisco State University and a visiting professor at Beijing Normal University, the University of St. Charles in Marseille, and Eotvos University in Budapest. Working with Unesco, Dan taught science education at universities in Peru, Egypt, Ghana, Ethiopia, Zimbabwe, Uganda and Kenya. Dan was in the "Homebrew Computer Club" with Steve Jobs and Steve Wozniak; everyone in that club became ultra-rich, except Dan.

The New Landscape of Data Acquisition and Signal Processing for FRB Research and The PANOSETI IR/Visible Ultra-Wide Field Nanosecond Time Scale Transient Search

First I'll discuss new architectures and open source hardware, gateware, and software for FRB instrumentation**.** For those new to instrumentation, I'll quickly review the CASPER open source technologies for rapidly building radio astronomy instruments such as correlators, beamformers, spectrometers, pulsar, and FRB machines.

Radio telescope arrays produce high data rates; a 1000 element array with 1 GHz bandwidth produces ~ 50 Terabits/second. Even single dish telescopes, especially those with wide-band feeds, multi-beam receivers, or phased array receivers, produce such high data rates that their data cannot be recorded or transported over internet to a remote computing facility. Most raw radio astronomy data must be processed in-situ.

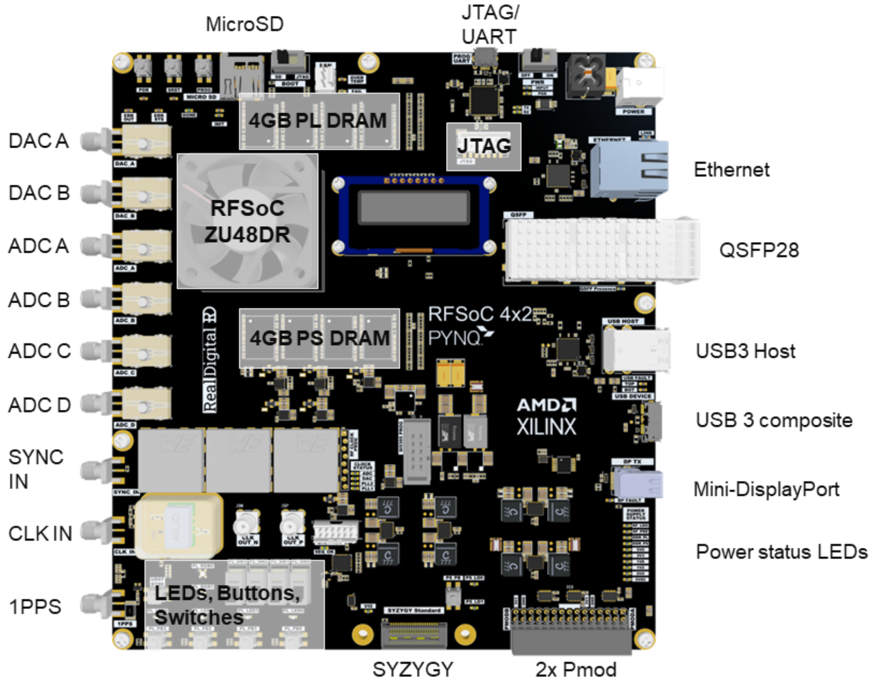
Early in-situ instruments developed by the Collaboration for Astronomy Signal Processing and Electronics Research (CASPER) were based largely on FPGAs (Field Programmable Gate Arrays). FPGA chips are good at signal processing, and more importantly, can handle very high data rates. FPGA chips handle ~1 Terabit/second. But FPGAs are hard to program and aren't good at floating point computation.

Today's radio astronomy instrumentation developers are shifting some or all signal processing computation to GPUs. GPUs are easier to program than FPGAs and are good at both floating point and integer signal processing. But GPUs have a bottleneck - getting high speed data in and out of the GPU can be very difficult. Almost all radio astronomy data processing applications on GPU's are I/O bound, not compute bound. Tensor cores on Nvidia GPU's are excellent at correlation, beamforming, and filtering; there are powerful codes for these radio astronomy applications, but we need to improve techniques to get high speed data into GPU. I'll talk about some of the new data transport techniques for getting high rate ethernet data into a GPU at rates to ~400 Gbit/second. By the way, tensor cores are not useful for FFT's, but more standard GPU processing elements can compute spectra and de-disperse efficiently, without tensor cores.

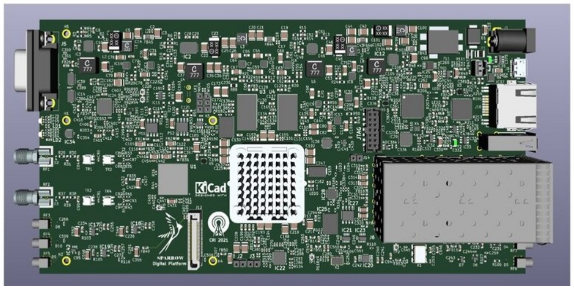
Since more radio astronomy signal processing computation is being shifted to accelerator boards (both FPGA and GPU accelerator boards), the CASPER collaboration has been working on inexpensive boards for digitizing signals, time stamping, and packetizing time domain ADC data. Some of these digitizer boards are pictured below.

For those new to radio astronomy instruments, the CASPER collaboration develops architectures and open source hardware, software, GPUware, FPGA gateware, tools, libraries, reference designs, tutorials, training videos, and workshops for radio astronomy instrumentation.
CASPER instrumentation is utilized mostly for radio astronomy, but also for physics, medicine, genomics, and engineering. More info at http://casper.berkeley.edu

The **PANOSETI** experiment searches a largely unexplored parameter space, observing a large field of view simultaneously (4,450 degrees) for nanosecond to second time scale transients at visible and near-IR wavelengths. The PANOSETI observatory employs two domes separated by ~1 km. Data from the two domes is cross-correlated to distinguish between astrophysical events and atmospheric phenomena (eg: Cherenkov radiation). Each PANOSETI dome contains ~45 telescopes; each telescope covers a 10 by 10 degree field. We have deployed a prototype PANOSETI observatory at Lick Observatory; we plan to build a full scale system at Lick or Palomar observatory. The small aperture, wide field-of-view, and low cost of the PANOSETI telescopes make them well-suited for high energy gamma-ray astronomy.



DIgitizer/Packetizer boards, which digitize signals, time stamp them, packetize, and transmit via ethernet. Left is $2,150 Xilinx RFSOC4x2 board, with four 5 Gsps 14 bit ADC's and 100Gbit ethernet. Lower left is low cost 10 watt dual 250 Msps 12 bit ADC Pika board developed by Lincoln Greenhill. Lower right is dual 500 Msps 12 bit ADC Sparrow board developed by Nima Razavi and Jack Hickish.



Physical Mechanisms of FRBs: Clues from Data and Progress in Theory

Bing Zhang (UNLV)

ABSTRACT

I will discuss three main questions regarding the physical mechanisms of FRBs using observational data, especially those collected from the FAST telescope, some of which are first reported. The topics include "What?", "Where?", and "How?". I will show predominant evidence of the magnetospheric origin of FRBs, discuss the production and propagation of FRBs, and comment on the pros and cons of the magnetar model and the possibility of other source types.

The main questions to understand the physical mechanisms of FRBs include: 1. What is (are) the source(s) of FRBs? The FRB 200428 detection suggests that magnetars can make FRBs, but can they do it all? 2. Within the magnetar scenario, where is the emission region of FRBs? Is it inside / slightly outside the magnetosphere (pulsar-like) or from relativistic shocks far from the central engine (GRB-like)? 3. How are FRBs with extremely high brightness temperatures made through one (or more) coherent radiation mechanism(s)? Answering these questions requires both observational data and theoretical insights and modeling. I will discuss these three questions in turn (with the "What?" question discussed in the end).

- **Where?** I will show the following predominant clues suggesting that FRBs originate from a region in the outer part (or slightly outside) the magnetosphere of a rotating central engine (a magnetar or something similar): 1. The two sub-bursts of FRB 200428 roughly coincide with the two X-ray peaks of the associated X-ray burst from SGR J1935+2154, and we know magnetar X-ray bursts are of a magnetospheric origin. 2. Even though the polarization angle (PA) within a single burst is consistent with being constant in some cases (which can be also explained in the magnetosphere models), cases of swinging PA with time within a burst have been observed in some bursts (both repeating or non-repeating), which demands a magnetospheric origin (Luo et al. 2022). 3. Thousands of bursts have been detected from a few active repeating FRBs (Li et al. 2021; Xu et al. 2022), sometimes with a burst rate > 500 per hour (Zhang et al. 2022). Clusters of FRBs (e.g. a cluster of 11 bursts within 0.2 s) have been discovered (Zhou et al. 2022). The short waiting time may be challenging for the synchrotron maser model but is not a problem for emission from a rotating magnetosphere. 4. The total burst energy emitted in month-timescale, when assuming a radio efficiency of $\eta \sim 10^{-5}$ and global beaming factor $f_b \sim 0.1$, already reaches several times 10^{46} erg, a significant fraction of the total magnetic energy of a magnetar (Li et al. 2021; Zhang et al. 2022). This requires more efficient radio emission and narrower beaming, which would be consistent with the magnetospheric origin. Alternatively, the source may not be a magnetar. There was a theoretical criticism that bright FRBs may not be able to escape a magnetar magnetosphere (Beloborodov 2021). However, a detailed study shows that bright FRBs can escape the magnetosphere under realistic FRB magnetosphere emission conditions that invoke a relativistic particle flow in the open field line region (Qu, Kumar, & Zhang 2022).

- **How?** A widely discussed magnetosphere FRB model is coherent curvature radiation by bunches. I discuss a new model that invokes coherent inverse Compton scattering by bunches (Zhang 2022). The hypothesis is that the crustal oscillation that drives Alfvén waves will also drive near-surface charge oscillations which will emit low-frequency electromagnetic waves. These waves can freely propagate through the magnetosphere and inverse-Compton scattered by relativistic particles in the charge starved region. The ICS emission power of a single electron is (7-8) orders of magnitude higher than that of curvature radiation.

The required degree of coherence is significantly reduced compared with curvature radiation. Radiation is highly linearly polarized. The emission has a narrow spectrum, consistent with observations.

- **What?** The active repeaters may or may not be magnetars. At least they reside in a dynamically evolving, highly magnetized environment, signified by rapid RM variation or even reversal (Xu et al. 2022; Anna-Thomaset al. 2022), possibly with a massive star or black hole companion. FRB host galaxies and redshift distribution are not consistent with tracking active star formation. Some older population sources are needed. Finally, a potential GW190425-FRB 20190425A association (Moroianuet al. 2022) is consistent with the production of a non-repeating FRB during the collapse of supramassive NS following a BNS merger (Zhang 2014) through the blitzar mechanism (Falcke & Rezzolla 2014).

Self-introduction:

Bing Zhang is a professor in the Department of Physics and Astronomy, the University of Nevada, Las Vegas (UNLV), and the Director of the Nevada Center for Astrophysics. He is a theorist actively collaborating with observers. He received his PhD degree in 1997 from Peking University, China. His PhD thesis and the work during the first two postdocs (Peking University/Australia, 1997-1998; NASA Goddard Space Flight Center (GSFC) 1998-2000) were on radiation mechanisms of pulsars. He started to work on theories of gamma-ray bursts (GRBs) in 2000 when he moved to Penn State University as a postdoc. He moved to UNLV in 2004, the same year when the NASA Swift mission was launched (with which he is affiliated). He spent most of his time understanding the physical mechanism of GRBs and other high-energy transients until recently when he shifts focus to FRBs, whose phenomenology and physical mechanisms mimic either pulsars or GRBs but also with significant differences. He is currently leading the FAST FRB Key Project to observationally study FRBs. One interesting experience was his 3-month visit to Australia back in 1998 hosted by Dick Manchester and Mathew Bailes (who just joined the faculty at Swinburne). His assigned job was to search for single radio pulses from Parkes archives. He made some progress but quit after receiving the offer from NASA GSFC. Later he was told that there were no FRBs from that archival data, so he was not particularly regretful for leaving the field for a substantial time.

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Evidence for Highly Relativistic Motion for the Crab Giant Pulses

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ABOUT THE AUTHOR

My interests cover much of astronomy but a focus on compact objects, stars and binaries, their structure, formation, and evolution, and their use to infer fundamental physical properties. My research is grounded in observations, but includes interpretation, theory, and numerical modelling. I generally try to make progress using key observations and/or physical considerations of individual, carefully selected objects.

My major focus has been to use neutron stars to study high-density and high field-strength physics, in conditions out of reach of terrestrial experiment (and theory, as yet), and to solve associated astronomical puzzles. I've become particularly intrigued by the possibilities of pico-arcsec astrometry offered by pulsar scintillation. We have started to try to apply this technique on pulsars, both to resolve emission regions and measure pulsar orbits on the sky.

I am also hoping to contribute to solving the mystery of FRBs, for which it seems likely neutron stars, possibly in binaries, are responsible. The nearest ones offer the best hope, as they are most suitable for follow-up at other wavelengths. In an effort to obtain accurate enough positions, I'm helping build an array of small, wide-field antennas, to observe in concert with CHIME.

RELEVANT RESULTS

The Crab Pulsar's radio emission is unusual, consisting predominantly of giant pulses, with durations of about a micro-second but structure down to the nano-second level, and extreme brightness temperatures. It is unclear how giant pulses are produced, but they likely originate near the pulsar's light cylinder, where corotating plasma approaches the speed of light.

I discuss observations where we use scattering in the Crab nebula to resolve not just the emission region giant pulses originate in, but also the region their constituent nanoshots are formed. We suggest that the simplest explanation for being able to resolve the emission regions, despite the short duration of giant pulses, is (apparent) superluminal motion.

In a different set of observations, shown in the figure overleaf, we appear to see direct evidence for Doppler shifts during the scattering tail of a giant pulse. From those, we infer that the plasma producing the giant pulses likely moves highly relativistically, with a Lorentz factor $\gamma \sim 10^4$, consistent with what is required for resolving the emission regions.

The above results support models that appeal to highly relativistic plasma to transform ambient magnetic structures to coherent GHz radio emission, be it for giant pulses or for potentially related sources, such as fast radio bursts.

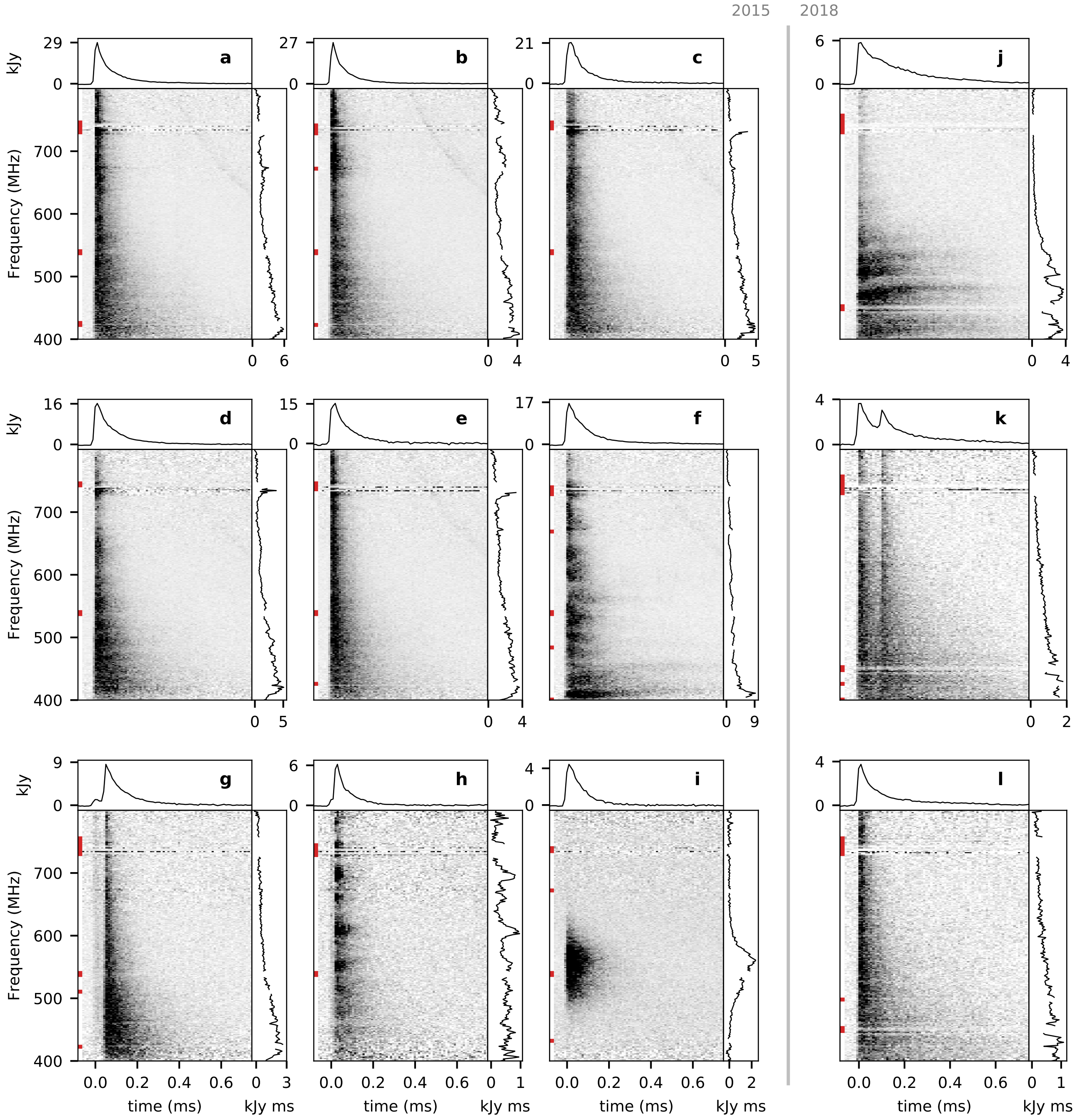

Figure 1. Dynamic spectra of 12 bright giant pulses of the Crab pulsar (taken from Bij et al., 2021, ApJ 920:38). Panels *a*–*f* and *j*–*l* are the brightest pulses in 2015 and 2018, respectively (ordered by descending brightness), while panels *g*–*i* are three further 2015 pulses chosen for their particular profiles. Pulse *j* stands out especially, with strong spectral bands that drift upward during the scattering tail. While the banding may simply reflect interference between nano-second scale giant pulse components, the variation is surprising, as in the scattering tail the only difference is that the source is observed via slightly longer paths, bent by about an arcsecond in the nebula. The corresponding small change in viewing angle could nevertheless reproduce the observed drift by a change in Doppler shift, if the plasma that emitted the giant pulses moved highly relativistically, with a Lorentz factor $\gamma \sim 10^4$ (and without much spread in γ).

Summary of the talk

The short, high-DM FRB sky in sharp view with Apertif

Joeri van Leeuwen

Identifying the physical nature of Fast Radio Burst (FRB) emitters arguably requires good localisation of more detections, and broadband studies enabled by real-time alerting. I will present the results, and lessons learned, from the Apertif FRB survey (ALERT) that ran 2019-2022. ALERT was powered by the Apertif Radio Transient System (ARTS), a supercomputing radio-telescope instrument that performs real-time FRB detection and localisation on the Westerbork Synthesis Radio Telescope (WSRT) interferometer. It reaches coherent-addition sensitivity over the entire field of the view of the primary-dish beam. We detected a new FRB every week of observing on average, interferometrically localised to ~0.4-10 sq.arcmin, leading to confident host associations (Fig. 1).

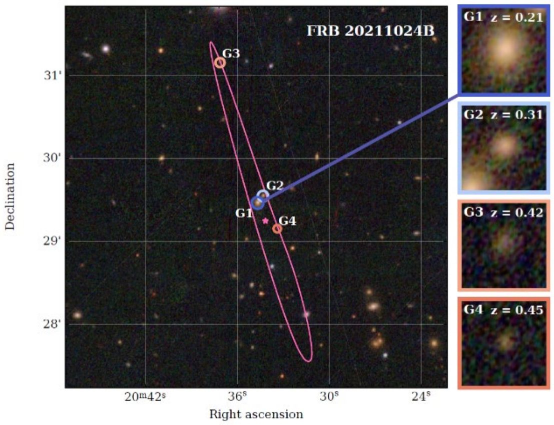

Figure 1: Localisation region and host of FRB 20211024B.

The 24 discovered FRBs broad band and very narrow, of order 1ms duration. Dispersion measures are generally high. Only through the "sharp" -- very high time and frequency resolution -- view of ARTS are these hard-to-find FRBs detected, producing an unbiased view of the intrinsic population properties. About a third of the FRBs display multiple components; a fraction much larger than the 5% found by CHIME/FRB at 600 MHz. We find this difference is not explained by increased scattering at lower frequencies alone, but is intrinsic.

Most Apertif localisation regions are small enough to rule out the presence of associated persistent radio sources. Three FRBs cut through the halos of Local Group galaxies M31 and M33 (Fig. 2).

We demonstrated that Apertif can localise one-off FRBs with an accuracy that maps magneto-ionic material along well-defined lines of sight. The solid detection rate next ensures a considerable number of new sources are detected for such study. The combination of detection rate and localisation accuracy exemplified by these ARTS FRBs thus marks a new phase in which a growing number of bursts can be used to probe our Universe.

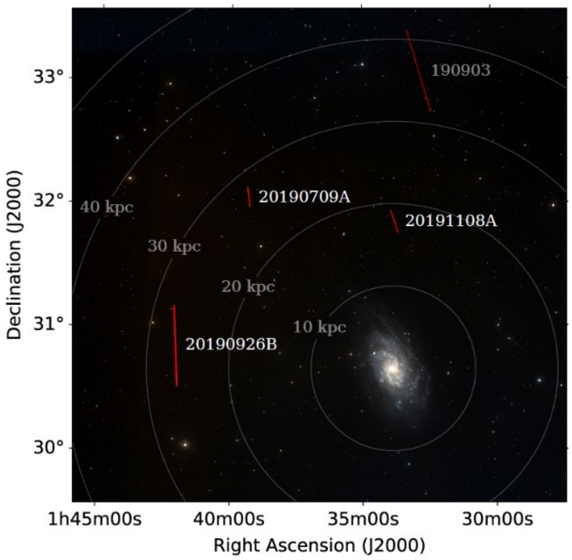

Figure 2: The location of the three FRBs + one candidate.

One of the Apertif bursts is the second most dispersed FRB known to date, and its rest frame shows FRB emission frequencies for one-offs reach 6 GHz. Repeaters had been seen up to 8 GHz before. FRB emission below 300 MHz had remained elusive, however. Using simultaneous Apertif-LOFAR radio data spanning over a factor 10 in wavelength, we show that periodically repeating FRB 20180916B emits down to 120 MHz and that its activity window is both narrower and earlier at higher frequencies. These results strongly disfavor scenarios in which absorption from strong stellar winds causes FRB periodicity. We establish that low-frequency FRB emission can escape the local medium. We thus demonstrate that some FRBs live in clean environments that do not absorb or scatter low-frequency radiation, a prerequisite for certain FRB applications to cosmology. Together, Apertif and LOFAR allow us to measure the activity in the FRB sky at multiple frequencies. For bursts of the same fluence, FRB 20180916B is more active at 150 MHz than at 1.4 GHz. We find there are 3–450 FRBs/sky/day above 50 Jy ms.

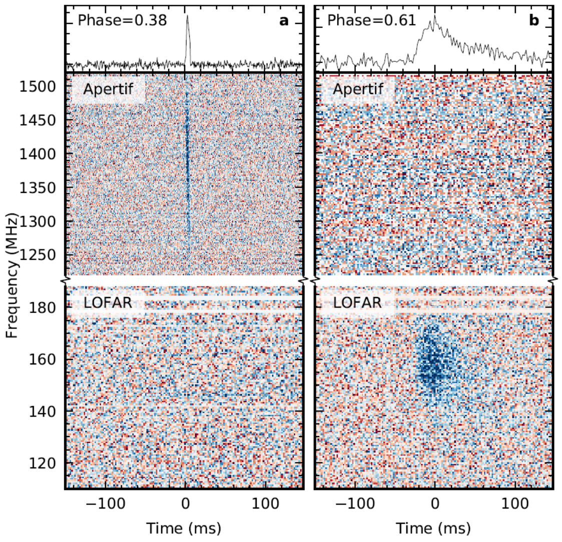

Figure 3: Two bursts at different phases. No burst was seen at both frequencies at the same time.

Self-introduction

I am Senior Astronomer at ASTRON, the Netherlands Institute for Radio Astronomy. I like to investigate transient phenomena in the Universe, through the design, execution and interpretation of dedicated radio-astronomical supercomputing experiments. My goal is to understand, a bit better, the space-time behavior plus the gargantuan densities and magnetic fields of pulsars, and perhaps the emission and explosions that occur near there.

I am (was ..?) the PI of Apertif, the wide-field high-speed radio cameras on the Westerbork Radio Telescope. Its integrated hybrid supercomputer is the largest data generator in The Netherlands.

I also lead CORTEX, a large Dutch academic-industrial consortium that makes self-learning machines faster. I am Editor for Astronomy & Computing, and an ERC Consolidator and an NWO Vici laureate. Also, winner of the triennial Willem de Graaff award for Outreach, from the Royal Netherlands Astronomical Society.

I like sports. Not watching though – only doing; especially with family or friends.