Multi-wavelength follow-up of fast radio bursts in the era of routine (sub)arcsecond localizations

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Talk titles and abstracts

April 25

Session 1

The astrophysics of FRBs
Daniele Michilli (MIT)

The origin of FRBs has been a critical question since their discovery in 2007. One essential piece to solving the puzzle is to measure their position in the sky. For example, thanks to both the spatial and temporal coincidence of an FRB and a flaring magnetar, it was possible to demonstrate that at least a part of FRBs is emitted by neutron stars. CHIME/FRB has also shown that with a large sample, even degree localization can be used to constrain the large-scale structures where FRBs reside. With arcminute localizations offered by CHIME/FRB, the closest FRBs have been pinpointed to their host galaxies in the local Universe, particularly useful to search for multiwavelength counterparts of nearby repeaters. More precise, arcsecond localization has been used to identify host galaxies up to higher redshifts, allowing multiple instruments such as ASKAP, VLA, MeerKAT, and DSA110 to study the properties of their host galaxies and to compare them with other astrophysical phenomena such as supernovae and gamma-ray bursts. The even larger sub-arcsecond precision of VLBI observations, such as that enabled by EVN, has been able to provide information about the position of FRBs within their host galaxies, further improving the comparison with other phenomena, and even imaging the local environment of FRBs at lower redshifts. In the next future, a leap in these studies is expected with the improvement of current instruments such as CHIME/FRB and ASKAP underway to localize hundreds of FRBs per year.

The Emergence of Fast Radio Bursts as Probes of the Universe
J. Xavier Prochaska (UCSC)

The fundamental signals inherent in FRBs – dispersion measure (DM), rotation measure (RM), and fluence – offer powerful constraints on properties of the plasma along the sightline to Earth. In turn, we may map out the cosmic web, constrain the density of gas surrounding galaxies, and infer the magnetic fields of the interstellar medium from a diverse population of galaxies. With ~50 FRBs localized over the past 5 years, this unique opportunity has transitioned from theory to reality. Now, as we head towards an order of magnitude increase in sample size (eventually two orders!), we must grapple with the biases, systematics, and theoretical shortcomings of our experiments. I will briefly review the scientific successes to date, highlight the “tall pole” challenges future advances, and discuss paths toward mitigation.

Session 2

Finding and localising FRBs with ASKAP/CRAFT
Ryan Shannon (Swinburne)

Our understanding of fast radio bursts (FRBs) has accelerated through the development of wide-field real-time FRB detection and localisation systems. The Commensal Real-time ASKAP Fast Transient (CRAFT) survey science project develops instrumentation to search for and localise FRBs using the 36-antenna Australian Square Kilometre Array Pathfinder (ASKAP), and currently searches for bursts in the incoherent sum of intensities from individual antennas and localises them to (sub) arcsecond precision using voltage buffers. This enables host galaxies to be identified and burst redshifts to be measured. In this presentation, I will review what we have learned from the 26 FRBs localised in these searches. I will describe and motivate the multi-wavelength follow up campaigns that we have undertaken, and what we have learned about FRB progenitors and emission mechanisms, the intergalactic medium, and cosmology from the discoveries. I will highlight challenges and opportunities for the field as larger samples of FRBs need to be followed up. I will conclude by describing progress on a new coherent FRB search system that we are currently commissioning for ASKAP that will increase the burst detection rate and enable it to probe a more distant FRB population.

From ad-hoc VLBI to EVN-light: PRECISEly localising FRBs with the longest baselines
Franz Kirsten (Chalmers)

Many of the repeating FRBs detected by CHIME/FRB are high enough in declination to be circumpolar for many of the telescopes in the European VLBI network (EVN). This makes them ideal targets for interferometric follow-up because scheduling observations is easy and very flexible. However, the EVN only runs three regular session per year, each lasting 2-3 weeks covering various frequency ranges. This is nowhere near enough observing time to catch bursts from repeaters. In late 2019, we started the PRECISE project in which we organised ad-hoc VLBI runs with a subset of EVN-dishes, using up to 750 telescope hours per year per dish. With this array, we detected and localised several FRBs, among which is the currently closest source, FRB 20200120E, that resides in a globular cluster in the spiral galaxy M81.

FRB localizations with the DSA-110
Liam Connor (Caltech)

Arcsecond localization of FRBs has proven essential for both progenitor science and cosmological applications. In the ~15 years following the Lorimer burst detection, fewer than two dozen sources were localized with sufficient precision to determine a host galaxy. With the Deep Synoptic Array (DSA-110) at OVRO, we have more than doubled this sample in the first year of commissioning. In my talk I will describe the DSA FRB survey and highlight early science results.

MeerTRAP: Real-time FRB detection and localisation with MeerKAT
Tiaan Bezuidenhout (North-West)

MeerTRAP is a European Research Council-funded project to look for single pulses from fast radio transients using the MeerKAT telescope in South Africa. Operating commensally with the eight MeerKAT Large Survey Projects (LSPs), we have amassed over 20,000 hours on sky of carrying out our search in real time. In addition to dozens of Galactic transients, this has led to the discovery of over 40 FRBs to date. MeerKAT's excellent sensitivity allows us to rapidly localise these sources to sub-arcsecond precision, and to establish host galaxy associations in some cases. In this talk, we showcase a number of MeerTRAP's FRB discoveries, with a focus on our localisation efforts. We also present the first results of our new instant imaging pipeline, which allows us to image and localise any transient as soon as a candidate event is triggered.

Thousands of VLBI Localizations with CHIME/FRB Outriggers
Kiyo Masui (MIT)

CHIME/FRB is currently the world's premier FRB instrument with a detection rate of nearly a thousand per year. However, CHIME only provides arcminute-scale localizations which limits followup opportunities to the nearest sources. The CHIME/FRB Outriggers project aims to overcome this limitation by adding three smaller telescopes located across North America that will localize CHIME-detected sources using very long baseline interferometry. I will provide an overview of the Outriggers project, including how it works, its current status, and its ultimate capabilities. The resulting sample of over a thousand ultra-precise localizations will be the premier targets for followup until next-generation facilities such as CHORD and DSA-2000 come online in the later part of the decade.

Fast and Fortunate for FRB Follow-up in the Era of Many Localized Events
Tarraneh Eftekhari (Northwestern)

The era of FRB science is poised to enter a new regime thanks to technical upgrades to a number of experiments which will provide subarcsecond localizations of FRBs at an unprecedented rate. This warrants dedicated follow-up efforts across the electromagnetic spectrum to maximize the scientific return from these precisely localized events, enabling detailed studies of FRB host galaxies and environments and leveraging their use as cosmological probes of the intergalactic medium. The Fast and Fortunate for FRB Follow-up (F4) collaboration, which partners with FRB experiments around the world, has already begun to lay the framework for such studies. In this talk, I will highlight recent scientific advancements from our collaboration, including the largest FRB host compilation study to date, constraints on the diffuse baryon content in galactic halos, searches for prompt optical counterparts, and radio to X-ray observations of FRB hosts as unique probes of the stellar populations driving FRB production. I will also discuss several efforts within the collaboration designed to streamline FRB follow-up in the era of many localized events and to provide publicly available host galaxy catalogs for the FRB community.

DWF: Fast transients and the nature of FRBs
Jeff Cooke (Swinburne)

The progenitors of FRBs and whether there exists more than one class is unclear. Detecting their counterparts is key to resolving their nature. The Deeper, Wider, Faster (DWF) program coordinates over 90 observatories located on every continent and in space, operating at all wavelengths (radio though gamma-ray) and particle detectors to detect fast (millisecond-to-day duration) transients, including FRBs and FRB counterparts. DWF operates proactively by coordinating the world's most sensitive wide-field facilities to perform deep, fast-cadenced observations of the same fields at the same time, taking data before, during, and after the fast-evolving bursts to capture multi-wavelength information before the events fade away. In addition, DWF performs real-time data analysis and transient identification and triggers rapid-response (minutes later) and later-time (hours/days later) follow up ground- and space-based spectroscopy and imaging as part of the program. As a result, DWF, in coordination with radio facilities offering real-time FRB localisation, provides the most promising route to detect FRB counterparts and understand their nature. I will briefly discuss the DWF program, some results to date, and future directions.

Session 3

Summary of multi-wavelength counterparts expected for different models
Ben Margalit (Berkeley)

The astrophysical origin and physical mechanism of fast radio bursts (FRBs) have been a mystery since their first discovery over a decade-and-a-half ago. Although dramatic progress has been made in recent years, there remain several viable FRB models and many unsolved questions in the field. Multi-wavelength constraints on FRB counterparts are a promising way to address these questions. In this talk I will give a summary of the multi-wavelength and multi-messenger counterparts to FRBs that are expected for different theoretical models. In discussing these expectations, I will distinguish between “associated counterparts” related to the FRB source or astrophysical progenitor, and “bona fide counterparts” to the radio emission of individual bursts. These promise to shed light on the origin and emission mechanism of FRBs, respectively.

Limits on Simultaneous and Delayed Optical Emission from Well-Localized Fast Radio Bursts
Daichi Hiramatsu (Harvard)

In this talk, I present the largest compilation to date of optical observations during and/or following a sample of 15 well-localized Fast Radio Bursts (FRBs), including 8 repeating and 7 one-off sources. Our simultaneous optical observations of 14 bursts from the recently-discovered, highly-active FRB 20220912A provide the deepest such limits to date for any extragalactic FRBs. These simultaneous limits provide useful constraints in the context of FRB models with prompt optical emission, such as the pulsar magnetosphere and pulsar nebula models. Interpreting all available optical limits for the FRB samples in the context of the afterglow emission from the synchrotron maser model, they are generally at least an order of magnitude larger than the energies inferred from the FRBs themselves, although in the case of FRB 20220912A, our simultaneous and rapid follow-up observations severely restrict the model parameter space. I conclude by exploring the potential of future simultaneous and rapid-response observations with large optical telescopes.

High-energy follow-up of FRB sources
Paul Scholz (UofT)

The origin of Fast Radio Bursts (FRBs) remains a mystery even as we are collecting important signs that point towards preferred source models. A key piece of the puzzle is the search for their multiwavelength counterparts. The detection of an FRB-like event from the Galactic magnetar SGR 1935+2154 with a simultaneous X-ray burst points to a magnetar origin for some FRBs, and such magnetar high-energy bursts may be detectable from nearby FRB sources. I will review current limits on high-energy counterparts and present our ongoing efforts to probe for X-ray counterparts to CHIME/FRB sources. I will put these efforts and other high-energy limits in context with magnetars and other models and what they can tell us about the nature of FRBs. I will then discuss how our follow-up strategies will change in the era of routine sub-arcsecond localizations.

Searches for Persistent Radio Counterparts to FRBs
Casey Law (Caltech)

The first FRB to be localized to arcsecond precision was associated with a persistent radio source (PRS). This source was peculiar not only for the association to an FRB, but for being compact (<1pc), luminous (>1e29 erg/s/Hz), and having a flat radio spectrum. These properties have been used to test models for FRB origin as well as constraining the age and energy of the FRB source. As new FRBs are discovered, new PRS have been detected and strict upper limits have been measured. This opens new questions about the potential for multiple origins for FRBs. At the same time, commensal instruments (realfast, MeerTRAP) and large radio surveys (VLASS, RACS, LoTSS) are increasing our ability to discover and study FRB radio counterparts. I will describe the state of the field in identifying persistent radio counterparts to FRBs and strategies for the > 1 FRB/day era.

Session 4

Host Galaxy Follow-up on a Population Scale: Lessons Learned from Supernova
Maria Drout (UofT)

With the advent of wide-field optical time domain surveys astronomers have moved from discovering dozens of supernova per year in the 1990s to tens of thousands per year in the 2020s. This has allowed population studies of both explosion properties and environments. Host galaxy studies, in particular, offer a useful means to probe the origin of classes of transients that are primarily detected at distances too large for direct identification of the progenitor stellar systems. This avenue of study has proved very fruitful in the area of supernova from the discovery of the different host galaxy preferences of thermonuclear, core-collapse, and super-luminous supernovae to trends in relative supernova rates with metallicity that provide important constraints for models of stellar evolution. In this talk, will review methods used by the supernova community to perform host galaxy follow-up as we transitioned from the era of individual object studies to population statistics. In particular, I will highlight types of data that have been most useful for specific science cases, challenges in our efforts to define unbiased samples, and other lessons learned for the FRB community.

Lessons Learned from Short Gamma-Ray Burst Follow-Up
Anya Nugent (Northwestern)

Current efforts to characterize the enigmatic progenitor of fast radio bursts (FRBs) are highly reminiscent of the early work to define the origins of short gamma-ray bursts (SGRBs), given that both transients are fast, luminous events that emit a “flash” in single part of the electromagnetic (EM) spectrum. With the advantage of 18 years of ~arcsecond SGRB localizations and a more conclusive neutron star merger origin for SGRBs, we derive lessons learned from the community follow-up of SGRBs; especially amidst the changing landscape of available resources (e.g. galaxy surveys), instrumentation, and knowledge of how these transients trace their host galaxy properties. In this talk, I will cover the scale of SGRB host galaxy follow-up and association as well as characterizing and comparing the hosts with uniform stellar population modeling. I will also discuss several unique cases of SGRBs and their hosts (highly offset SGRBs and faint host galaxies) and how they significantly impact our understanding of the environments in which SGRBs can occur. Finally, I will note how we can apply these lessons in the upcoming era of detecting many FRBs per week across a wide range of capable facilities.

Telescope Follow-up of Gravitational Wave Events: Strategies and Lessons Learned
John Ruan (Bishop's)

Gravitational waves from compact object mergers are now routinely detected, and many large collaborations have formed to perform telescope follow-up of the localization regions across the electromagnetic spectrum. I will briefly describe follow-up strategies currently employed or being developed for three gravitational wave experiments: LIGO, Pulsar Timing Arrays, and LISA. Electromagnetic follow-up for these experiments each have their own unique challenges, and I will highlight analogies to FRB follow-up.

April 26

Session 1

What do the redshifts of FRB host galaxies tell us?
Clancy James (Curtin)

This talk will summarise what FRB host galaxy redshifts tell us about the redshift evolution of FRB progenitors, and how the resulting two-dimensional distribution of z and DM is used in fitting both cosmological and FRB population parameters. I'll also focus on how systematic effects, such as the difficulty of optically identifying distant FRB hosts, the tendency for repeating FRBs to be preferentially localised, and uncertainties in the frequency-dependence of FRBs, affects these estimates.

How will (locations in) host galaxies help solve the mystery of FRBs?
Alexandra Mannings (UCSC)

The origins of FRBs remain an outstanding question and tantalizing mystery. Each time we uncover something new, we have even more questions about the intricacies of their origins — comparing variations in host properties and looking for ever elusive patterns. With only a few dozen FRBs with sub-arcsecond localizations, we have already glimpsed the powerful information we can find through characterizing the environments of FRBs within their hosts. Imagine what can be done with hundreds and even thousands! With examples set by studies of other transient events such as Type-1a and Core-collapse supernovae, and gamma ray bursts, characterizing locations of FRBs relative to star-forming regions, compact radio sources, and more can illuminate possible progenitor pathways. This talk will detail some of the ways that we can utilize high-resolution imaging and various analyses of new FRB hosts to find answers.

Session 2

The host galaxies and local environments of fast radio bursts
Shivani Bhandari (ASTRON/JIVE)

Fast Radio Bursts (FRBs) are millisecond-duration transients of intense, coherent radiation that are signposts of extreme astronomical environments. Despite 15 years of research, no conclusive consensus on the progenitor(s) of FRBs has been reached. While it is clear that some FRBs might be produced by magnetars, the diversity of FRB properties, behaviours, and locations implies that this is not the complete answer. Although there has been significant progress in localising FRBs to their hosts, we are still only scratching the surface in terms of the locations in which we can find FRBs. In this talk, I will give an outline of our current understanding of FRB host galaxies and their local surroundings.

The Dark Energy Spectroscopic Instrument (DESI): An Overview
Dustin Lang (Perimeter)

I'll briefly introduce the Dark Energy Spectroscopic Instrument (DESI) and its ongoing surveys. DESI is a 5000-fiber multi-object spectrograph that is mapping tens of millions of galaxies. I will focus on the footprint, status/timeline, and data quality as it relates to FRB Follow-up efforts (or, more likely, as an archival host-galaxy redshift-lookup resource).

LSST and Exploring the Fast Frontier of the Time-Domain
Gautham Narayan (Illinois)

The Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST) will survey 18,000 sq. degrees of sky every three nights, with an even higher cadence in a subset of fields. Together with the emerging network of ground- and space-based wide-field optical facilities, LSST will enable astrophysicists to probe the next frontier of the time-domain, going not just deeper or redder, but faster. And amongst the fast transient phenomena that have been discovered or predicted, fast radio bursts (FRBs) are some of the most exciting. I will summarize the LSST survey and its current status in commissioning, describe our work in LSST's Dark Energy Science Collaboration (DESC) to combine multiple datasets together to maximize the available information of the transient and variable Universe, talk about how we might be able to follow-up FRB detections from CHIME, and eventually DSA and other radio facilities, and discuss how we can make progress with simulations and testing right now, to prepare for first light at Rubin Observatory.

SPHEREx: An All-Sky Spectral Survey
Michael Zemcov (RIT)

SPHEREx is a NASA mid-class Explorer Mission that will perform the first all-sky spectral survey at near-infrared wavelengths. Beginning in early 2025, SPHEREx will obtain 0.75-to-5μm spectra of every 6.2 arcsec pixel on the sky with spectral resolution $R>41.5$ and a 5σ sensitivity $AB>19$ per spectral/spatial resolution element over a two-year mission. The SPHEREx team plans to perform three specific science investigations: (1) map the large-scale structure of galaxies to study the inflationary birth of the universe; (2) determine the abundance of interstellar water and organic ices available to proto-planetary systems; and (3) measure the light produced by stars and galaxies over cosmic history. The SPHEREx survey will provide unique all-sky spectral information including spectra of very large numbers of extragalactic, galactic, and solar system targets, including not just point-like but also both extended and diffuse sources. This dataset will quickly become available to the global astronomical community to enable a staggering range of science. In this talk I will review SPHEREx's purpose, design, planned operations, and highlight the properties of the dataset that make its contribution unique in the coming decade of large surveys.

Session 3

A measurement of circumgalactic gas around nearby galaxies using fast radio bursts
Xiaohan Wu (CITA)

The distribution of gas in the circumgalactic medium (CGM) of galaxies of all types is poorly constrained. Foreground CGMs contribute an extra amount to the dispersion measure (DM) of fast radio bursts (FRB). We measure this DM excess for the CGMs of $10^{11}-10^{13}\ M_\odot$ halos using the CHIME/FRB first data release, a halo mass range that is challenging to probe in any other way. Because of the uncertainty in the FRBs' angular coordinates, only for nearby galaxies is the localization sufficient to confidently associate them with intersecting any foreground halo. Thus we stack on galaxies within 80 Mpc, optimizing the stacking scheme to approximately minimize the stack's variance and marginalize over uncertainties in FRB locations. The sample has 20-30 FRBs intersecting halos with masses of $10^{11}-10^{12}\ M_\odot$ and also of $10^{12}-10^{13}\ M_\odot$, and these intersections allow a marginal $1-2\,\sigma$ detection of the DM excess in both mass bins. The $10^{11}-10^{12}\ M_\odot$ halos bin also shows a DM excess at 1-2 virial radii. By comparing data with different models for the CGM gas profile, we find that all models are favored by the data up to 2-σ level compared to the null hypothesis of no DM excess. With 3000 more bursts from a future CHIME data release, we project a 4-σ detection of the CGM. Distinguishing between viable CGM models by stacking FRBs with CHIME-like localization would require tens of thousands of bursts.

FRBs as Probes of Cosmology and Fundamental Physics

Jon Sievers (McGill)

While the origin of fast radio bursts (FRBs) may remain mysterious, the precise arrival timing across broad frequency bands nevertheless enables them as probes of the universe. The (redshift-weighted) line-of-sight electron column density is exquisitely measured by each FRB, which lets us use them to probe the ionized baryon density. At low redshifts, we can map out the baryon density independent of temperature and density, which enables FRBs to probe the "missing baryons", structure of galaxy clusters, and break degeneracies in kinetic Sunyaev-Zeldovich effect (kSZ) measurements from the cosmic microwave background (CMB). At higher redshifts, FRBs could be used to probe the evolution of the ionization fraction during reionization, enabling an independent measurement of the reionization optical depth (tau) measured by the CMB. This measurement would be robust to foreground contamination.

The precise arrival timing of FRBs across ~octave bandwidths also enables probing the photon mass and the equivalence principle. Already, limits from FRBs on the photon rest mass are comparable to the best direct measurements, and future data should improve this limit by an order of magnitude or more.