A SYNOPTIC VIEW OF FAST TRANSIENTS WITH CHIME AND RUBIN

STEVE KAHN SYMPOSIUM
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WHAT ARE FAST RADIO BURSTS

artwork: Jingchuan Yu, Beijing Planetarium
FAST RADIO BURSTS

• Single radio flashes that are:
  
• Brief (~ milliseconds)
  
• Broad band (observed from 0.2 to 8 GHz)
  
• Bright, ~1 - 100 Jy (1 Jy = 10^{-26} W/m²/Hz)
  
• Few percent are repeating sources, majority are one-offs
  
• Cosmologically distant, but typically poorly localized
RELATED TO NEUTRON STARS?
DISPERSION

image: Erik Madsen
DISPERSION

\[ t_d \propto DM \lambda^2 \]

\[ \text{DM} = \int_{\text{src}}^{\text{obs}} n_e d\vec{s} \]

\[ [\text{DM}] = \text{pc/cm}^3 \]

image: Erik Madsen
$DM = \int_{src}^{obs} n_e d\vec{s}$
DM VS Z
MACQUART RELATION

\[ DM_{\text{cosmic}}(z) \text{ Planck15 cosmology} \]

- FRB 180924
- FRB 181112
- FRB 190102
- FRB 190608
- FRB 190711
- FRB 121102
- FRB 190523
- FRB 190611
~50 observed from 2007-2017 but ~thousands/sky/day
We need a larger sample
TO GET A BIGGER SAMPLE WE NEED

A new kind of radio telescope
WHAT LIMITS THESE?
NEW TECHNOLOGY

WHAT HAS CHANGED?

KIYOSHI MASUI
Artist’s Impression of SKA Low
CHIME

- Digitally driven telescope operating from 400 to 800 MHz
- Large field of view, high sensitivity.
- Detects ~1000 FRBs/year (~50/year for all others combined)
COMMENSALITY

- CHIME ‘points’ digitally, and data can be copied
- Correlator can feeds backends for multiple commensal surveys:
  - 21 cm intensity mapping
  - Fast radio burst (FRB) search
  - 21 cm absorption system search
  - Multiplexed pulsar timing
  - Slow pulsar search
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PROGRESS ON PROGENITORS

Detection at low frequencies

Subpopulation of sources that emit repeat bursts

A repeater that is active on a 16-day period

An FRB with 100 ms quasi-periodicity

A repeater near a star-forming region of a nearby galaxy

A repeater in a globular cluster in M81

A fast radio burst emitted from a Galactic magnetar

KIYOSHI MASUI
FRB FROM GALACTIC SOURCE SGR1935+2154

CHIME/FRB

Simultaneous X-rays (Konus-Wind)

G1 + G2
18 - 320 keV
SGR RADIO BURST WAS FRB-LIKE

Flux > 100 kJy

Spectral Luminosity [erg s⁻¹ Hz⁻¹]

Transient Duration (ν W) [GHz s]
(MOST) CLUES POINT TO MAGNETARS

• Young neutron stars powered by energy stored in extremely strong magnetic fields

• Favored sources because of:
  • Direct association (SGR 1935+2154)
  • Energetics
  • Short time scales
  • Association with star formation
  • Periodic activity from binary orbit or precession
ASIDE: FAST OPTICAL BURSTS?

CHIME/FRB

Simultaneous X-rays (Konus-Wind)

G1 + G2

18 - 320 keV
Rubin's 15s + 15s sequential exposures opens the "fast" discovery space

Still pay 15s / 1ms in extra background, but Rubin wins by etendue

Guillem Megias Homar, Meyers, Kahn, 2023
SOURCE ENVIRONMENTS OF REPEATERS

FRB 20180916 (R3)

z = 0.034 spiral galaxy
Marcote et al. 2020, Nature

60 pc from a star forming region
Tendulkar et al. 2021
SOURCE ENVIRONMENTS OF REPEATERS

Outskirts of M81
Bhardwaj et al. 2021

An M81 halo globular cluster!
Kristin et al. 2022, Nature
Evidence from source localizations/environments mixed on magnetar hypothesis

But only a few data points...
CHIME/FRB VLBI OUTRIGGERS
CHIME’S WEAKNESS: RESOLUTION

Typical localization uncertainty ~1 arcmin
TWO TYPES OF LOCALIZATION

Traditional interferometry
~1 arcsecond
Mannings et al. 2021

VLBI
~milliarcsecond
Tendulkar et al. 2021
CHIME/FRB VLBI OUTRIGGERS

Outrigger Station

KKO 100 km Dominion Radio Astrophysical Observatory

Hat Creek Radio Observatory

Green Bank Observatory

Outrigger Station

3300 km
• Each outrigger about 1/8 CHIME collecting area

• “Rolled” reflectors but otherwise nearly identical optical, analog, and digital systems
GOAL:

Localize Every CHIME-Detected FRB (few thousand) to < 50 mas
THE CHALLENGE:

We don’t know where or when our VLBI target is
SYNOPTIC TRANSIENT VLBI

- Data rate for phase-preserving data:
  - fundamental scaling $\sim$ FOV $\times$ Collecting area $\times$ Bandwidth
  - CHIME data rate 100x EHT station

- Calibration (clock synchronization and the ionosphere):
  - Don’t know when or where on the sky to calibrate
  - Need an always-ready calibration solution
HAPPENING NOW IN BC

k’niʔatn k’l stk’masqt Outrigger (KKO)
Name kindly offered by the Upper Similkameen Indian Band
Listening device for outer space

Photo: NRC
HAPPENING NOW IN GREEN BANK

Photo: Kevin Bandura
STARTING IN A FEW MONTHS:

Thousands of FRBs, with DMs, localizations, host galaxies, redshifts
Rubin will be critical to understanding source environments
RUBIN IMAGING OF FRB HOSTS/ENVIRONMENTS

• 50 mas localizations only useful with deep colorful imaging with good seeing

• LSST and CHIME have ~4000 sq. deg. of sky overlap: hundreds of FRBs
FRBS IN THE LSST FOOTPRINT WILL HAVE:

- Deepest imaging for identifying faint (dwarf) hosts
- Most reliable host photo-z’s
- Deepest images with excellent seeing for associating sources with substructures
- Six filter photometry for measuring source environment properties
We will know everything there is to know about FRB source environments with CHIME, CHIME/FRB outriggers, and Rubin.
HOW TO USE FRBS AS

COSMOLOGICAL PROBES
Counts every free electron along line of sight (baryons ~90% ionized)

\[ t_d \propto DM \lambda^2 \]

\[ DM = \int_{\text{src}}^{\text{obs}} n_e d\vec{s} \]

\[ [DM] = \text{pc/cm}^3 \]

image: Erik Madsen
WHY ARE BARYONS SO POORLY CONSTRAINED

- Supernova and AGN feedback processes in galaxy formation are complex
- Single AGN can throw a baryon ~ megaparsecs
- This *is* the missing baryon problem:
  - IGM contains most of the baryons
  - Cannot be observed, cannot be reliably simulated
  - So we don’t know precisely where in the IGM they are
HOW CAN FRBS HELP?

By measuring statistically where the IGM is by proxy of the free electrons

Furthermore, can measure where the IGM is in relation to the (red, blue) galaxies
A CRUCIAL INPUT TO RUBIN WEAK LENSING

• The IGM contaminates weak gravitational lensing (Nicola et al. 2022)

• IGM is 14% of the matter, power spectrum is order-of-magnitude uncertain on Mpc scales

• Lensing entangles spatial scales through line-of-sight integral

• Unless we understand feedback, can’t do percent-level measurements of dark matter/dark energy

• With external (FRB) measurement of baryon-CDM cross-power, can interpret lensing on much smaller scales
CHIME AND RUBIN WILL WORK TOGETHER FOR THIS MEASUREMENT

- Most complete sample of photo-z’s for both FRB hosts, foreground galaxies to cross-correlate
- Speculatively - could cross-correlate FRB DM with lensing mass, measure matter-baryon cross-power
OTHER REASONS COSMOLOGY NEEDS THIS

• Baryons interact gravitationally with dark matter making it hard to tease out dark matter physics from structure formation.

• Measuring electrons breaks a key degeneracy in the CMB kinematic Sunyaev–Zeldovich (KSZ) effect (Madhavacheril et al. 2019).
CONCLUSIONS

• Fast radio bursts are a mysterious high-energy phenomena; from CHIME, magnetar progenitor favored but evidence mixed

• VLBI Outriggers and Rubin imaging/photometry will soon provide localizations, redshifts, and source environments

• FRBs and Rubin data will (finally) measure the large-scale baryon distribution, solving a key uncertainty in large-scale structure formation, decontaminating lensing from baryons