New approach to observational astronomy to solve the nature of FRBs

Jeff Cooke and the DWF team
What are FRBs?

Need to detect them

Need to localise them

Then what?

Follow up Nothing so far, must be fast or faint

Host galaxy?

Doesn’t give us the nature of the event

EM emission? Wavelength? Particles? GW?

Coherent flux?

Need to be on source before the radio
What is needed

**Simultaneous detection efforts** –
All wavelengths, high energy particles, GWs
*Deep, wide-field, fast-cadence*

**Real-time data processing and analysis**
Seconds to minutes identification
Software and human confirmation

**Rapid-response triggered observations**
Deep, multi-wavelength imaging and spectroscopy

**Follow-up cadenced observations**
Important for confirmation and classification
What we have

**Multi-wavelength, multi-messenger detection**
- All wavelengths
- High energy particles
- Gravitational waves

**Deep** simultaneous observations
- The world’s largest, most sensitive telescopes
  - $100,000 per night, 10:1 oversubscription, etc.

**Wide** field of view instruments
- The largest and best in the world

**Fast**-cadenced observations
- Millisecond to seconds observations
Deeper, Wider, Faster program
DWF

(1) Simultaneous coverage

- All wavelengths and messengers
  - Worldwide coordination

- Multiple radio facilities to detect FRBs
  - Multiple frequencies to get spectral index, info

- Dense imaging coverage
  - Characterising their evolution

- Cross-matching of all wavelengths
  - Learn what they are
Parkes
Swift
Molonglo
simultaneous obs
DECam
Legend
\*\* simultaneous obs
early 2015
mid 2016

Legend
- simultaneous obs
- rapid response, ToO, long-term follow up
- opposite side of Earth
mid 2017

DWF-Pacific

U Tokyo

XMM-Newton
Fermi
Swift

ASKAP
MWA
Zadko

ATCA
AAT
LCOGT
ANU2.3m
Huntsman
SkyMapper
Parkes
Molonglo

DREAMS

IceCube
AST3–2
AST3–3

Legend
- simultaneous obs
- rapid response, ToO, long-term follow up
- proposed/upcoming/future
- opposite side of Earth
DECam   Parkes   Molonglo

Swift BAT

Fields of view
DECam, Parkes, Molonglo

AAT
2dF+AAOmega
392 spectra

SkyMapper, CNEOST

AST3-2, TNTS

Swift BAT

Subaru
Hyper
SuprimeCam

XRT, UVOT, Zadko, GROND, MLO, ATCA, AST-3, ~30 other facilities
What DWF is

We are a full detection program and follow up

LIGO–Hanford, LIGO–Livingston, Virgo, GEO600, MWA, Molonglo, ASKAP, ATCA, Parkes, VLA, MeerKAT, GROND, REM, Gattini
Keck, SALT, HET, Subaru, VLT, Gemini, Palomar, CTIO, AAT, Lick, ANU 2.3m, Lijiang, Xinglong, ASV, SkyMapper, LCOGT, Kiso, CNEOST, TNTS, MLO, Zadko, AST3–2, VIRT, La Hita, Huntsman, Panetix
Swift, HXMT
Pierre Auger, HAWC

Future: Green Bank, APEX, LMT, VISTA, GOTO, Liverpool, VST, CFHT, ASTROSAT, XMM–Newton, HESS, MAGIC, FACT
What DWF has

(2) Real time data processing and analysis

Events are fast
   Need to identify them before they fade

Swinburne supercomputer
   Smart people to code

Candidate analysis
   Software and human inspection

Fast analysis
   Hundreds of candidates in minutes, continuously
g2 gSTAR SwinSTAR
Real-time analysis - Dec 2015, Jul/Aug 2016

Movie
Real-time analysis - Feb 2017
Real-time analysis

This candidate is ID6136, observed in the 'Artilia' field on 02/02/2017. It is number 5 of 13 you have selected. The auto-ranker has assigned it a ranking 5/5, where 5 is most interesting and 1 is least interesting.

If anyone else has entered notes on this object into the database, they will appear here:
Fast transient

**Movie**

min = 0.0

credit: Andreoni

ID = dwf16 9497
Extragalactic novae

NCG 6744
10 Mpc
What DWF has

(3) **Rapid-response triggers (minutes)**

Events are fast
  Can acquire them quickly before they fade

Events are faint
  We have the largest telescopes in the world

The Earth is round and turns
  Telescopes are all over the world (*and in space*)

Coordination and collaboration
  All types of facilities, institutions, collaborators
Some of the DWF facilities
What DWF has

(4) Conventional and longer-TERM follow up

Some FRB models predict association with slower-evolving events

Confirm transient nature
   Variable, repeat?

The Earth is round and turns
   We have a network of telescopes all over the world (and in space)

Coordination and collaboration
   All types of facilities, institutions, collaborators
Most recent DWF run

Last night end of 4 night run
DWF “war room” control room at Swinburne for 2018 onwards
Objects found during the latest DWF run

Shown is the $\sim 1.8 \text{ deg}^2$ field of view of the Subaru Hyper SuprimeCam imager

Detections down to mag $\sim 25$ in 30 seconds
Zoom in of a region - objects forming lines are asteroids
DWF summary

The fast time domain is essentially \textit{unexplored territory}.

Multi-facility, multi-wavelength global collaborative effort is the only means to capture and study FRBs and understand their nature.

DWF is the first program to achieve this aim:
- Simultaneous, fast-cadenced multi-wavelength detection facility
- Real-time reduction, analysis, and candidate identification
- Rapid-response triggered spectroscopy and imaging
- Long-term monitoring to classify associated slower events, etc.

DWF can resolve the nature of FRBs in a "\textit{single shot}"
The main idea of the text is that there is a close relationship between gravitational wave searches and electromagnetic searches. In the past six years, systematic searches have been conducted by various organizations, and new classes of transients have been identified. The governing physics is still being debated, and it is expected that detecting gravitational waves from neutron star mergers every month will become routine. A basic commonality between gravitational wave searches and the electromagnetic search described above is that we only knew about three classes (denoted by gray bands). In the past six years, systematic searches, such as those by the Palomar Transient Factory and P60-FasTING (Kasliwal et al. 2011a), have contributed to the identification of various classes of transients. Therefore, prior to the ambitious search for an electromagnetic counterpart to a gravitational wave signal, it would only be prudent to build a complete inventory of transients in the local Universe.

![Graph showing the relationship between characteristic timescale and peak luminosity for various transient events.](Image)

The graph illustrates the relationship between characteristic timescale and peak luminosity, with different transient events represented by colored bands. The x-axis shows the log of the characteristic timescale in seconds, while the y-axis shows the peak luminosity in erg s⁻¹. The graph includes various transient events such as GRBs, Type Ia supernovae, core-collapse supernovae, and others, each represented by a specific band color.

The key points highlighted in the graph are:

- **GRBs**: Gravitational wave bursts, shown in red, are represented in the log (Characteristic Timescale) range of 1.5 to 3.0. The peak luminosity for GRBs ranges from 10⁴⁵ to 10⁴⁶ erg s⁻¹.

- **Type Ia Supernovae**: These are denoted by a green band, with characteristic timescales ranging from 10⁻² to 10⁻¹ days and peak luminosities from 10⁴⁰ to 10⁴¹ erg s⁻¹.

- **Core-Collapse Supernovae**: Represented by a blue band, these have characteristic timescales ranging from 10⁻³ to 10⁻² days and peak luminosities from 10⁴¹ to 10⁴² erg s⁻¹.

- **Kilonovae and Mergers**: These events are shown in purple, with characteristic timescales ranging from 10⁻⁴ to 10⁻³ days and peak luminosities from 10³⁸ to 10⁴⁰ erg s⁻¹.

- **Soft Gamma-Ray Repeaters**: These have characteristic timescales from 10⁻⁶ to 10⁻⁵ days and peak luminosities from 10³⁶ to 10³⁷ erg s⁻¹.

- **Ultra-Luminous X-Ray Outbursts**: Located in the lower left corner, with characteristic timescales from 10⁻⁸ to 10⁻⁶ days and peak luminosities from 10³³ to 10³⁴ erg s⁻¹.

- **Flare Stars**: Represented in the lower right corner, with characteristic timescales from 10⁻¹ to 1 day and peak luminosities from 10³⁸ to 10⁴⁰ erg s⁻¹.

- **X-Ray Binaries**: These have characteristic timescales from 10⁻³ to 10⁰ days and peak luminosities from 10³⁶ to 10³⁹ erg s⁻¹.

The graph provides a visual representation of the diversity of transient events and their relationship with the characteristic timescale and peak luminosity.
distant sample of SMBHs, which in turn, hold the greatest promise of extending the existing M-σ relation beyond current limitations by revealing dormant SMBHs in galactic nuclei [15,16].

Finally is the class of unknown transients for which we currently lack both predictions and detections. This class represents a significant area of discovery space that only a wide-field and sensitive X-ray transient "machine" can uniquely explore. In the sections below, we outline the importance of extending our knowledge of known, predicted, and unknown X-ray transients, on par with the on-going ground-based technological efforts to advance our understanding of the dynamic sky at optical (LSST) and radio (SKA pathfinders) wavelengths.

Figure 1: A compilation of high energy transients that are known (solid) and/or predicted (hatched) in the local (d< 200 Mpc) Universe. The variability timescale is the characteristic duration of the transient outburst, plotted here as a function of the peak X-ray luminosity during the outburst. Transients with variability on multiple timescales are linked with dashed lines. Sub-luminous, fast (< 10 sec), and rare transients have historically been missed due to instrumentation limitations. Characteristics compiled from references [1-6,9-14,16,19-23].

A Diversity of X-ray Transients

The dynamic nature of the local X-ray Universe was established decades ago, revealing diverse classes of outbursting objects (Figures 1 & 2). In particular, those transients with long duty cycles (> months), high peak luminosities (L_X > 10^{37} erg/s) and/or large populations (> 100s per galaxy) were the first to be detected, catalogued and studied. At the same time, Soderberg (2010)
Figure 1. Time-luminosity phase space for known radio transients from Cores (2009); log - log plot of the product of peak flux density $S_{pk}$ in Jy and the square of the distance $D$ in kpc vs. the product of frequency $\nu$ in GHz and pulse width $W$ in s. The uncertainty limit on the left indicates that $\nu W > 1$ follows from the uncertainty principle. Lines of constant brightness temperature $T_b = S D^2 / 2 k (\nu W)^2$ are shown, where $k$ is Boltzmann’s constant. Points are shown for the nano-giant pulses detected from the Crab, giant pulses detected from the Crab pulsar and a few millisecond pulsars, and single pulses from other pulsars. Points are shown for Jovian and solar bursts, flares from stars, brown dwarfs, OH masers, and AGNs. The regions labeled coherent and incoherent are separated by the canonical $10^{12}$ Kelvin effect that is relevant to incoherent synchrotron sources. The growing number of recent discoveries of transients illustrates the fact that empty regions of the $\nu W - S_{pk} D^2$ plane may be populated with sources not yet discovered. The figure also includes hypothetical transient sources and detection curves; e.g. maximal giant pulse emission from pulsars, prompt radio emission from GRBs, bursts from evaporating black holes, and radar signals used to track potentially impacting asteroids and comets in exosystems. Long-dashed lines indicate the detection threshold for the full SKA for sources at distances of 10 kpc and 3 Gpc. Dotted and dot-dashed lines correspond to the current and future GMRT at 1.2 GHz (i.e. bandwidth of 32 MHz and 400 MHz, respectively). At a given $\nu W$, our sources have luminosity above the line detectable. The curves assume optimal detection (matched filtering).
Figure 4. The framework of cosmic explosions in the year 2011 (Kasliwal 2011). Note that until 2005 (Fig. 1), the localization of the gravitational wave signal and consequent large false positive rate of electromagnetic counterparts to gravitational wave signals limited the search for gravitational waves from neutron star mergers every month to become routine. A basic commonality between gravitational wave searches and the electromagnetic search described above is that they both are limited to the local Universe (say, < 200 Mpc). A known challenge will be the poor sky localization of the gravitational wave signal and consequent large false positive rate of electromagnetic counterparts to gravitational wave signals.

In order to achieve a complete inventory of transients in the local Universe, it would only be prudent to build this.

Several classes of transients can be identified based on their unique properties and timescales:

1. **Core-collapse supernova shock breakout** (PTF09cnd, SN2005ap, SN2006gy, etc.)

2. **Supernovae** (SN2007bi, SN2008S, etc.)

3. **Red novae** (M31 RV, V838 Mon, etc.)

4. **Classical novae** (M81OT, 081119, etc.)

5. **Calcium-rich halo transients** (helium deflagrations?)

6. **.Ia Explosions** (helium detonations in ultra-compact white dwarf binaries)

7. **Pair instability explosions** (helium detonations in white dwarf binaries)

8. **Luminous supernovae** (magnetars)

9. **Magnetic candidates** (Kulkarni & Kasliwal 2009)

Detecting gravitational waves from neutron star mergers every month is expected to become routine. A basic commonality between gravitational wave searches and the electromagnetic search described above is that they both are limited to the local Universe (say, < 200 Mpc). Therefore, prior to the ambitious search for an electromagnetic counterpart to a gravitational wave signal, it would only be prudent to build this complete inventory of transients in the local Universe.
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