A new approach to observational astronomy to detect the fastest transients and solve the nature of FRBs

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on behalf of Jeff Cooke and the DWF team
Fast transients

Events with millisecond-to-hours duration

Include very early detections and fast time-sampling of longer duration events

Occur at all wavelengths + particle + gravitational waves
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. 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. 

A known challenge will be the poor sky albedo between gravitational wave searches and the electromagnetic search described above is that both are limited to the local Universe (say, 20 Mpc). A known challenge will be the poor sky albedo between gravitational wave searches and the electromagnetic search described above is that both are limited to the local Universe (say, 20 Mpc).

New classes are emerging and the governing physics is being widely debated: luminous red novae (electron capture induced collapse of rapidly rotating O–Ne–Mg white dwarfs?), luminous supernovae (magnetars or pair instability explosions?), .Ia explosions (helium detonations in ultra-compact white dwarf binaries), Calcium-rich halo transients (helium deflagrations?). 

In the past six years, systematic searches, discoveries by the Palomar Transient Factory and P60-FasTING (Kasliwal et al. 2011a) are denoted by the serendipitous discoveries and archival searches have uncovered a plethora of novel, rare transients. Discoveries by the Palomar Transient Factory and P60-FasTING (Kasliwal et al. 2011a) are denoted by serendipitous discoveries and archival searches have uncovered a plethora of novel, rare transients.


CHARACTERISTIC TIMESCALE [day] vs. PEAK LUMINOSITY [M_V]

The characteristic timescale of the transients ranges from 0.1 to 100 days, and the peak luminosity ranges from 10^10 to 10^24 erg s^-1. The characteristic timescale of the transients ranges from 0.1 to 100 days, and the peak luminosity ranges from 10^10 to 10^24 erg s^-1. 


The figure by Kasliwal (2011) provides a framework of cosmic explosions in the year 2011. Note that until 2005 (Fig. 1), we only knew about three classes (denoted by gray bands). In the past six years, systematic searches, discoveries by the Palomar Transient Factory and P60-FasTING (Kasliwal et al. 2011a) are denoted by serendipitous discoveries and archival searches have uncovered a plethora of novel, rare transients.
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 both are limited to the local Universe (say, 300 million light years or 300 Mpc). A known challenge will be the poor sky localizations of the gravitational wave signal and consequent large false positive rate of electromagnetic counterparts to a gravitational wave signal, it would only be prudent to build this framework of Cosmic Explosions in the Year 2011 (Kasliwal 2011). Note that until 2005 (Fig. 1), we only knew about three classes (denoted by gray bands). In the past six years, systematic searches, serendipitous discoveries and archival searches have uncovered a plethora of novel, rare transients. Discoveries include calcium-rich halo transients (helium deflagrations?), Ia explosions (helium detonations in ultra-compact white dwarf binaries), and pair instability explosions?

Ia Explosions

Core-Collapse

Supernovae

Luminous Supernovae

Classical Novae

Red Novae

Luminous Red

Novae

Thermonuclear

Supernovae

Ca-rich

Transients

PTF09dav

PTF10fqs

PTF11bij

PTF10iuv

PTF09cwl

PTF09cnd

PTF09atu

PTF10cwr

PTF10bhp

V838 Mon

NGC300OT

M81OT

SN2002bj

SN2005E

SN2005ap

SN2007bi

M31 RV

M85 OT

SN2006gy

SN2008ha

SN2008S

M81OT

M82OT

M85 OT

V838 Mon

Transients in the local Universe

![Fast transients (optical)](chart)

**Figure 4.** Framework of Cosmic Explosions in the Year 2011 (Kasliwal 2011). Note that until 2005 (Fig. 1), we only knew about three classes (denoted by gray bands). In the past six years, systematic searches, serendipitous discoveries and archival searches have uncovered a plethora of novel, rare transients.
Figure 4. Framework of Cosmic Explosions in the Year 2011 (Kasliwal 2011). Note that until 2005 (Fig. 1), serendipitous discoveries and archival searches have uncovered a plethora of novel, rare transients. Discoveries by the Palomar Transient Factory and P60-FasTING (Kasliwal et al. 2011a) are denoted by a small icon. Several types of transients are emerging and the governing physics is being widely debated: luminous red novae (electron capture induced collapse of rapidly rotating O–Ne–Mg white dwarfs?), luminous supernovae (magnetars), and serendipitous discoveries and archival searches have uncovered a plethora of novel, rare transients. Detecting gravitational waves from neutron star mergers every month is expected to become routine. A basic common framework of the observed phenomena (advanced LIGO, advanced VIRGO, LCGT, INDIGO) coming online. 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.
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)
Searches for radio transients

Figure 1. Time-luminosity phase space for known radio transients from Cordes (2009); log log \( S_{pk} \) 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 \( T_b = S D^2 / 2k(\nu W)^2 \) are shown, where \( k \) is Boltzmann’s constant. Points are shown for the nano-giant pulse 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 region labeled coherent and incoherent is separated by the canonical 10^{12} K limit from the inverse Compton 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 source 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 \( \nu W \), as our sources have luminosity above the line to detect. The curves assume optimal detection (matched filtering).
Short focus on fast radio bursts (FRBs)

Unknown nature so far - as many theories as theorists

Solving the mystery

Need facilities to detect them and, ideally, localise them

Then what?

Programs have triggered ‘reactive’ follow up (*hours to days later*)

Nothing so far, perhaps fast and/or faint (*FRBs detected to z ~ 2*)

Host galaxy detections

Doesn’t give us the nature of the event

EM emission evolution? Which wavelength? Particles? GW?

Coherent flux? If so, shorter wavelengths arrive Earth before radio

Need to be ‘proactive’ - on source *before*, during, and after the radio detection
Fast transients (in general)

**Occur at all wavelengths**
- Some only in one wavelength regime
- Others at multiple or all wavelengths
- Some unknown wavelengths (*i.e.*, FRB counterparts)
- Some include high-energy particles and gravitational waves

**Need to act fast to catch them, work fast to ID them**
- Fast exposures needed to sample their evolution
- Simultaneous all-wavelength coverage before they fade
- Need to process and analyse data fast, and identify events fast, for follow up before they fade
- Need deep rapid-response spectroscopy and imaging

All this needs to be done in minutes (or faster) from the moment the light hits the telescopes
What is needed

1. Coordinated simultaneous detection

2. Real-time data processing and identification

3. Rapid-response and conventional ToOs

4. Longer-term cadenced observations
What we have

(1) Coordinated simultaneous detection
   Deep, wide-field, fast-cadenced observations, ~20 of the world’s best telescopes. All wavelengths + particles + GWs

(2) Real-time data processing and identification
   Fast data transfer, supercomputer processing (seconds/minutes)
   Software and human identification and confirmation (in minutes)

(3) Rapid-response and conventional ToOs
   Deep, multi-wavelength RTO/ToO spectroscopy and imaging
   ~10 space-based and 1-10m class ground-based telescopes

(4) Longer-term cadenced observations
   Network of ~30 follow-up telescopes (1-10m class)
   Important for confirmation, classification, host galaxies, etc.
   (Some fast transients are associated with longer duration events)
Deeper, Wider, Faster program
2015 - 2016

• Successfully coordinated simultaneous Parkes & Molonglo (radio), DECam (optical), and Swift (UV/x-ray/GR) observations

• Developed flexible ‘lossy’ file compression to speed up transfer and maintain >98% success in candidate identification
  
  Vohl et al., 2017, PASA, 34, 38

• Developed and refined real-time parallel data processing on the Swinburne supercomputer

• Generalised pipeline for transient detection (here, for use with CTIO DECam and Subaru Hyper Suprime-Cam)

  Andreoni et al., 2017, PASA, 34, 37

• Progressed real-time data visualisation technology for human transient candidate inspection (confirmation for triggers)

  Meade et al., 2017, PASA, 34, 23
mid 2016

Legend
- simultaneous obs
- rapid response, ToO, long-term follow up
- opposite side of Earth
What DWF is

A full ‘proactive’ detection program and a full follow up program

Facilities 2017/2018 (future/planned facilities in grey):

GWs: LIGO-Hanford, LIGO-Livingston, Virgo, GEO600

Radio: MWA, Molonglo, ASKAP, ATCA, Parkes, VLA, MeerKAT, Green Bank

Sub-mm: LMT, APEX

Infrared: GROND, REM, Gattini, VISTA, DREAMS, AST3-3

Optical: Keck, SALT, Subaru, VLT, Gemini, Palomar, CTIO Blanco, AAT, Lick, ANU 2.3m, Lijiang, Xinglong, ASV, SkyMapper, LCOGT, KISO, CNEOST, TNTS, MLO, Zadko, AST3-2, VIRT, Panetix, La Hita, Huntsman, CFHT, Liverpool, VST

U/X/G: Swift, HXMT, XMM-Newton, ASTROSAT, MAXI

High-E: Pierre Auger, HAWC, HESS, MAGIC, FACT
DWF-Pacific

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

ATCA, AAT, LCOGT, Parkes, Molonglo, Panetix, Swift, KISO, CNEOST, Xinglong, Lijiang, Subaru, LIGO-WA, LIGO-LA, Virgo, Lick, Gattini, VLA, HAWC, LCOGT, DWF-Pacific, HXMT, GROND, REM, VLT, DECam, Panetix, Palomar, MLO, VLA, Gattini, DECam, REM, Gemini, GROND, Pierre Auger
(1) Coordinated simultaneous detection

Deep, wide-field, fast-cadenced *observations*, ~20 of the world’s best telescopes. All wavelengths + particles + GWs
Fields of view

DECam

Parkes

Molonglo

Swift BAT

AAT
2dF+AAOmega
392 spectra

Subaru
Hyper
SuprimeCam

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

AST3-2,
TNTS

SkyMapper,
CNEOST
(2) **Real-time data processing and identification**

Fast data transfer, supercomputer processing *(seconds/minutes)*

Software and human identification and confirmation *(in minutes)*
The vast majority of the world's communications are not carried by satellites but an altogether older technology: cables under the earth's oceans. As a ship accidentally wipes out Asia's net access, this map shows how we rely on collections of wires of less than 10cm diameter to link us all together.

‘Lossy’ compression code
Vohl et al., 2017, PASA, 34, 37
Swinburne supercomputer

g2
Real-time analysis – Feb 2017
Real-time analysis – Feb 2017
This candidate is ID6136, observed in the Antlia 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:
min = 0.0

credit: Andreoni
min = 0.0

credit: Andreoni
Extragalactic novae

NCG 6744
10 Mpc
(3) Rapid-response and conventional ToOs

Deep, multi-wavelength RTO/ToO spectroscopy and imaging

~10 space-based and 1-10m class ground-based telescopes
Some of the DWF facilities
(4) Longer-term cadenced observations

Network of ~30 follow-up telescopes (1-10m class)
Important for confirmation, classification, host galaxies, etc.
Some fast transients are associated with longer duration events
Identify all bursts within minutes after the light hits the telescopes.

Data transfer (about a minute)

Data processed in about a minute

High-energy bursts

Seconds

Radio bursts

Trigger follow up

Blanco telescope

Swinburne Supercomputer

Visualisation room

Gemini-South
Objects found during a DWF run

DECam detections to mag ~ 23.5 in 20 seconds
Zoom in of a region

Objects forming lines are asteroids
Serendipitous discoveries and archival searches have uncovered a plethora of novel, rare transients. Discoveries of 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 both are limited to the local Universe (say, within 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.

Previously, we only knew about three classes (denoted by gray bands). In the past six years, systematic searches, both with dedicated instruments on the ground and in space, have opened up completely new possibilities. A complete inventory of transients in the local Universe is desirable. This will allow us to test cosmic models and their parameters. Any new classes are emerging and the governing physics is being widely debated: luminous red novae (electron capture induced collapse of rapidly rotating O–Ne–Mg white dwarfs?), luminous supernovae (magnetars or pair instability explosions?), Ia explosions (helium detonations in ultra-compact white dwarf binaries), or calcium-rich halo transients (helium deflagrations?).
Data visualisation

Fast transient candidates require human inspection and confirmation prior to triggering rapid-response and other ToO observations. We use interactive projectors to examine hundreds of candidates every few minutes as the data are continuously processed (soon VR). We use an interactive web-based analysis tool to help identify events in real time – participants are located worldwide. We use 4K tiled wall displays to examine the full CCDs, search for artifacts, examine transient environments, cross-talk, etc.

Data sonification

We use pitch, volume, timbre, and stereo (soon 3-D) to help enhance and accelerate analysis, leading to more confident identifications. We are exploring higher-order harmonics and “the cocktail party” effect to explore multi-parameter space and low S/N ratio data. Cooke et al., 2018, IAU 339 Conf. Proceedings
DWF summary (part 1)

The fast time domain is largely \textit{unexplored territory}

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

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”}
DWF summary (part 2)

- A unique and creative use of DECam
- Characterising the fast transient Universe
- Trailblazing science for LSST
- Pioneering a new observational approach
  - Simultaneous multi-wavelength/multi-messenger observations
  - Real-time data processing
  - Exploring advances in transient rapid identification invoking machine learning and creative techniques
  - Exploring data visualisation and sonification to enhance and accelerate Big Data analysis and transient confirmation
  - Largest global collaboration to acquire simultaneous data and perform rapid-response follow up