Multi-wavelength follow-ups for FRBs

The case of SUPERB FRBs

Shivani Bhandari
PhD student, Swinburne University
FRB Conference, Aspen, 2017
Outline

• Efforts for FRB searching in real-time
  • Introduction to SUPERB and survey specifications
  • SUPERB data processing pipelines
  • New FRB detections

• Multi-wavelength follow-ups

• Why multi-wavelength follow-up is important?
  • The rise and fall of J071634.59-190039.2
  • FRB 131104: Gamma ray association and the unusual variable radio source

• Current strategies and Discussion
SURVEY FOR PULSARS AND EXTRA-GALACTIC RADIO BURSTS

- Finding FRBs in real time
- Effecting multi-wavelength follow-ups
- Understanding nature and origin of FRBs
Specifications

• SUPERB is scheduled to spend ~130 days searching for FRBs.
• ~80% of the survey is done.

Survey specifications
– 64 us time resolution
– ~9 minutes per pointing
– 400 MHz bandwidth, 1024 channels
– DM smearing: 1.3 ms for a DM of 1000 units
SUPERB data processing pipelines

- Transient and periodicity searches.
- There are two data pipelines
  - Fast pipeline: Real-time processing
  - Thorough pipeline: Offline processing

<table>
<thead>
<tr>
<th>Parameter</th>
<th>F pipeline</th>
<th>T pipeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM range (pc cm(^{-3}))</td>
<td>0–5000</td>
<td>0–9988</td>
</tr>
<tr>
<td>DM trials, (N_{DM})</td>
<td>1749</td>
<td>1986</td>
</tr>
<tr>
<td>Width trials</td>
<td>((1 - 2^{10}) \times t_{samp, DM})</td>
<td>((1 - 2^{12}) \times t_{samp, DM})</td>
</tr>
<tr>
<td>RFI excision methods</td>
<td>Bad channels</td>
<td>eigenvector excision</td>
</tr>
</tbody>
</table>

Keane et al. 2017 (in prep)
Real time processing
Single pulse search

- Data acquisition and RFI flagging
- HEIMDALL – Box car convolution algorithm
- Coincidence filtering

\[
\frac{S}{N} \geq 10 \\
N_{\text{beams}} \leq 4 \\
N_{\text{events}}(t_{\text{obs}} - 2 \text{ s} \rightarrow t_{\text{obs}} + 2 \text{ s}) \leq 5
\]

FRB candidates

Pulsar candidates from single pulse search

\[
\text{DM} \geq 1.5 \times DM_{\text{Galaxy}} \\
W \leq 16.384 \text{ ms}
\]

Keane et al. 2017 (in prep)
**FRB Detections**

<table>
<thead>
<tr>
<th>SNR</th>
<th>Time</th>
<th>DM</th>
<th>Length</th>
<th>Beam</th>
<th>Known Source(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.5571</td>
<td>471.66</td>
<td>774.723</td>
<td>1.024</td>
<td>04</td>
<td></td>
</tr>
</tbody>
</table>

**Beams Positions & Known Sources**

<table>
<thead>
<tr>
<th>Beam</th>
<th>RA</th>
<th>DEC</th>
<th>GI</th>
<th>Gb</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>07:17:28.3</td>
<td>-19:28:08.7</td>
<td>233.16997547</td>
<td>-3.2600178939</td>
</tr>
<tr>
<td>02</td>
<td>07:16:22.4</td>
<td>-19:52:44.6</td>
<td>233.41381672</td>
<td>-3.6792507366</td>
</tr>
<tr>
<td>03</td>
<td>07:15:25.0</td>
<td>-19:26:58.0</td>
<td>232.92805616</td>
<td>-3.6803552890</td>
</tr>
<tr>
<td>04</td>
<td>07:16:30.9</td>
<td>-19:02:24.4</td>
<td>232.68442586</td>
<td>-3.2610104572</td>
</tr>
<tr>
<td>05</td>
<td>07:18:33.9</td>
<td>-19:03:31.4</td>
<td>232.92637377</td>
<td>-2.8407264687</td>
</tr>
<tr>
<td>06</td>
<td>07:19:31.6</td>
<td>-19:29:13.3</td>
<td>232.41169448</td>
<td>-2.839618867</td>
</tr>
<tr>
<td>07</td>
<td>07:18:25.0</td>
<td>-19:53:51.0</td>
<td>233.65552280</td>
<td>-3.2587968426</td>
</tr>
<tr>
<td>08</td>
<td>07:17:19.0</td>
<td>-20:18:51.5</td>
<td>233.90496614</td>
<td>-3.6809846212</td>
</tr>
<tr>
<td>09</td>
<td>07:14:17.4</td>
<td>-19:51:42.4</td>
<td>233.17911666</td>
<td>-4.1058511689</td>
</tr>
<tr>
<td>10</td>
<td>07:14:26.6</td>
<td>-19:01:00.3</td>
<td>232.43691718</td>
<td>-3.684379815</td>
</tr>
<tr>
<td>11</td>
<td>07:17:36.5</td>
<td>-18:37:25.0</td>
<td>232.43560046</td>
<td>-2.8385186410</td>
</tr>
<tr>
<td>12</td>
<td>07:20:38.3</td>
<td>-19:04:22.7</td>
<td>233.1680439</td>
<td>-2.4141821187</td>
</tr>
<tr>
<td>13</td>
<td>07:20:30.0</td>
<td>-19:55:05.8</td>
<td>233.9024127</td>
<td>-2.835175025</td>
</tr>
</tbody>
</table>

**Plots**

Superb mailing list
Superb@lists.pulsarastronomy.net
http://lists.pulsarastronomy.net/mailman/listinfo/superb_lists.pulsarastronomy.net

2 Attachments
Multi-wavelength synergies
Christmas and New Year FRBs

#fireworks in the radio sky

Bhandari et al. 2017 (in prep)
Polarisation for FRB 160102

FRB 160102 – 100% polarised
RM = -220.6 +/- 6.4 rad m^{-2}

Caleb & Bhandari et al. 2017 (in prep)
How many high RM continuum extragalactic radio sources are there in the Universe? 

NOT MANY!

Adapted from Hammond et al. 2013
Young and expanding SNRs?

PIRO (2016)
Possible progenitors

• Young and expanding SNRs (Piro 2016)
• Young SNR pulsars (Connor et al. 2015)
• Supergiant pulses from extragalactic neutron stars (Cordes et al. 2015)
• Magnetars (Popov et al. 2013)

Connor et al. 2015.
Multi-wavelength follow-up campaign

Image credit: NASA.
Follow-up campaign
Any hints in radio follow-ups?

Observations

• **ATCA**
  – 42 pointing mosaics encompassing Parkes 15’ FWHM
  – C band 2 IFs – center freqs: 5.5 GHz and 7.5 GHz
  – Best RMS ~ 40 uJy/beam

• **GMRT**
  – L band – center freq: 1.4 GHz
  – Best RMS ~ 30 uJy/beam

• **VLA**
  – 7 pointing mosaics encompassing Parkes 15’ FWHM
  – C band – center freq: 5.9 GHz
  – Best RMS ~ 10 uJy/beam

Image credit: NRAO.
Any hints in radio images?

Results: FRB 151230

Variability and transient criteria from Rowlinson et al 2016
Any hints in radio images?
Results: FRB 160102

Sources in FRB 160102 field

I am significant!
ATCAS4
ATCAS4 details

• This source is identified to be a quasar in the HMQ catalog (Flesch E. 2015).
• It is also identified in GALEX and has a DSS (optical) counterpart.
Did FRBs repeat?

- NO REPEATS in 3 hours
- NO REPEATS in 16 hours
- NO REPEATS in 11 hours
- NO REPEATS in 14 hours
- NO REPEATS in 48 hours
Optical follow-ups

• Thai National Telescope (TNT) – FRB 151206
  – FOV = 8’X8’
  – r’ band 5 sigma detection limit ~ 22.0
  – 5 variable sources – maximum delta mag ~ + 0.5
  – Stellar variability.

• Subaru – FRB 151230
  – g, r and i band, 5 sigma detection limits ~ 25
  – 2 AGNs in field
  – No optical transients
Optical follow-up conti..

• DECam – FRB 151230
  – FOV ~ 3 deg²
  – u, g, r and i band; i band 5 sigma detection limits ~ 22.5
  – 4 asteroids and 1 unidentified transient.

• Zadko – FRB 151230 shadowing!
  – FOV ~ 23’X23’
  – Limiting r band magnitude ~ 19.8
  – Asteroids
  – No convincing variables/transients!
Optical follow-up results

- Variability attributed to stellar variability, AGN variability or presence of asteroids.
- No optical afterglows with limiting magnitude I mag ~ 25.0 and R mag ~ 22.0
- Cadence under investigation: minutes, days to week.
X-ray follow-up

- Triggered for FRB 151230 and FRB 160102.
- FRB 151230
  - No sources detected above 3 sigma
  - limiting flux $\sim 1.9E-13$ erg/cm$^2$/s
- FRB 160102
  - No sources detected above 3 sigma
  - limiting flux $\sim 1.4E-13$ erg/cm$^2$/s
SUMMARY I

SUPERB FRBs

- SUPERB - three new FRB discoveries.
- FRB 160102 is ~100% polarised.
- No significant transients in radio, optical or x-ray in any of the three FRB fields.
- ATCAS4 is a significantly variable source detected in the FRB 160102 field.
- None of the FRBs have repeated yet in 92 (21+52+19) hours of follow-up!
Why multi-wavelength follow-ups?
FRB detections!
The phase of real-time detections and multi-wavelength follow-ups

The rise and fall of J071634.59-190039.2

Keane et al. 2016
Williams & Berger 2016
Vedantham et al. 2016

Bassa et al. 2016

Giroletti et al. 2016

Johnston et al. 2016
FRB 131104
Gamma ray association and unusual radio variable

DeLaunay et al 2016

A Coincident AGN flare (Shannon et al. 2016)
FRB121102
The Repeater!

FRB 121102 – Direct FRB localisation co-located with radio source. (Chatterjee et al 2017)
Why multi-wavelength follow-ups?

To identify host galaxies and progenitors of FRBs thus probing cosmology!
Current strategy

Triggering telescopes to observe FRB field as soon as possible after the detection.

ADVANTAGES
• Highly effective collaboration in place
• Shadowing observations
• Exploring unknowns
• Learning from non-detections

DISADVANTAGES
• Manual Triggering
• Use of large telescope time
• Blind searches

What is the optimal strategy?
Deeper, Wider, Faster
(as of July 2016, now 80+ members, 28 institutions)

PI: Jeff Cooke
Radio: Emily Petroff, Chris Flynn, Manisha Caleb, Shivani Bhandari, Evan Keane, Stuart Ryder, Wael Farah, Fabian Jankowski, Vivek Venkatraman Krishnan, Themiya Nanayakkara, Aditya Parthasarathy, Sarah Burke-Spolaor, Casey Law
Optical: Tyler Pritchard, Tim Abbott, Chris Curtin, Stephanie Bernard, Chuck Horst, Mansi Kasliwal, David Coward, the SkyMapper team, the Zadko team, and the Gemini–South and SALT support astronomers
UV/x-ray/gamma-ray: Tyler Pritchard, Igor Andreoni, Amy Lien, Neil Gehrels
Real-time processing: Igor Andreoni, Tyler Pritchard, Armin Rest, Alex Codoreanu, Phil Cowperthwaite, Chuck Horst
Data Science: Dany Vohl, Colin Jacobs, Vincent Morello
Visualization: Bernard Meade, Chris Fluke, Dany Vohl, Sarah Hegarty

1 Swinburne 2 ASTRON/NIRA 3 ANU 4 University of Manchester/SKAO 5 AAO 6 NRAO 7 CTIO/NOAO 8 University of Melbourne 9 San Diego State University 10 Caltech 11 UWA 12 STScI 13 NASA/GSFC 14 Harvard University 15 University of Bonn 16 Maria Mitchell Observatory 17 University of Edinburgh
DWF will solve the overall nature of FRBs in "one shot" with

- simultaneous, deep, multi-wavelength, fast-cadenced light curves
  before, during, and after the FRB detection
  (radio localisation, spectral index
  search for IR, optical, UV, x-ray, gamma-ray emission)
- real-time (seconds) radio, optical, gamma-ray data processing and analysis
- real-time (minutes) software and visual transient identification
- rapid-response 'flash' 8m-class spectroscopy (in minutes)
  (deep spectrum of event and host galaxy)
- rapid-response multi-wavelength imaging (in minutes)
- conventional spectroscopic and imaging ToOs
  (search for association with longer-duration event)
- gravitational wave and neutrino detectors (via MoUs)
- long-term follow-up with a network of 1–10m telescopes
Collect simultaneous data (continuous 20s integrations), transfer it, process, calibrate and analyse it, and identify candidates every ~1 minute.
Discussions

• What do we learn from current follow-ups?
  • No optical/radio/x-ray afterglows?
  • FRBs related to extremely variable AGNs?
  • FRBs originating in Dwarf galaxies?
  • Do all FRBs repeat?
  • Variability analysis vs direct imaging.

• What is the optimal follow-up strategies?
  • Telescopes on the field as soon as possible after FRB detection?
  • Follow-up approach with reduced localisation error upon detection?
  • Extensive follow-up only upon a FRB host detection?
  • Targeted selection in FRB fields
  • Telescopes on the field before a detection? (Deeper Wider Faster)