The localization of a repeating Fast Radio Burst

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Introduction

Fast Radio Bursts

Possible origins

The only repeater, FRB 121102

The first and only precise localization of a FRB

Persistent counterparts

Discussion & Conclusions

Summary from FRB 121102

The future for Fast Radio Bursts
Introduction
Introduction: What is a Fast Radio Burst?

- Fast and strong radio flashes
- Duration of a few milliseconds
- Bright: $\sim 0.1$–$1$ Jy
- Detected at radio freq. ($\sim 1$ GHz)
- Discovered by Lorimer et al. (2007)
- Origin: unknown

FRB 140514
Introduction: What is a Fast Radio Burst?

- 30 FRBs have been reported to date
  Petroff et al. (2016)

- Poor localizations (∼ arcmin)
  No associations

- Typical observing frequency: 1.4 GHz

- No correlation with the Galactic Plane

- Rate: \( \sim 10^{3-4} \text{ sky}^{-1} \text{ day}^{-1} \)
The Dispersion Measure

Light is dispersed by the material in the medium.

Dispersion Measure:

\[ DM = \int n_e \, d\ell \propto \nu^{-2} \]

All FRBs show unexpected large DMs.

Much larger than the contribution of our Galaxy

Estimated \( z \sim 0.16–1.3 \)

Lorimer et al. (2007)
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Lorimer et al. (2007)
What can FRBs be?

Credit: J. P. Macquart
Extra-Galactic

Implied rate of 1000s per day, per sky... but what are they?

Galactic

We are here

Pernicious RFI
Atmospheric effects

Credit: Jason Hessels
The only repeater, FRB 121102
The repeater FRB 121102

- The only one discovered by Arecibo (305-m diameter)
- The only repeater: Spitler et al. (2014, 2016), Scholz et al. (2016)
- In the Galactic anticenter
- No periodicities
  Active periods?
- One of the closest ones?
  \( \text{DM} \sim 560 \, \text{pc cm}^{-3} \)
  (\( \times 3 \) Galactic contribution)
- Two types of FRBs?
Chatterjee et al. (2017, Nature, 541, 58)
Marcote et al. (2017, ApJL, 834, 8)
The precise localization of FRB 121102

Karl G. Jansky Very Large Array (VLA)
- 27 25-m dishes
- \( \sim 100 \) km apart
- From Nov 2015 to Sep 2016
- 83 h at 1.6 and 3 GHz
- One burst on 23 Aug 2016
- 8 more in Sep 2016

Real-time correlation + raw data buffering to search for pulses

European VLBI Network (EVN)
- 6–10 stations (Europe, Asia, Africa)
- \( \sim 10000 \) km apart
- From Feb to Sep 2016
- 8 epochs at 1.6 and 5.0 GHz
- 4 bursts on 20 Sep 2016
5-ms image (dispersion corrected) of one burst.

Chatterjee et al. (2017, Nature, 541, 58)
The VLA localization of FRB 121102

- Persistent radio and optical counterparts
- $z = 0.19273(8) \rightarrow 972$ Mpc
- Co-located within $\sim 0.1$ arcsec
- Variability $\sim 10\%$
- Variability uncorrelated with bursts
  - $L_{\text{persistent}} = 3 \times 10^{38}$ erg s$^{-1}$
  - $L_{\text{bursts}} \sim 10^{42}$ erg s$^{-1}$

Chatterjee et al. (2017, Nature, 541, 58)
but... are the bursts and the persistent counterpart physically related?
Localizing FRB 121102 on milliarcsecond scales

The EVN observations

- 4 bursts on 20 Sep 2016
  - The brightest one: $\sim 4$ Jy
  - The other three $\sim 0.2$–$0.5$ Jy

- Arrival times obtained from Ar data
  - Bursts also detected in other EVN stations
  - Coherently de-dispersion
  - Correlation with higher time resolution around the pulses
  - Calibration from the continuum data

- Images of bursts and persistent source

Marcote et al. (2017, ApJL, 834, 8)
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Dirty and clean image from FRB 121102.

Astrometry limited by signal-to-noise ratio

Positions derived from 406 pulses from the pulsar B0525+21

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Localizing FRB 121102 on milliarcsecond scales

**colorscale:** 5-GHz image

**Contours:** 1.7-GHz image

(Bursts observed at 1.7 GHz)

+: brightest burst

+: other bursts

+: average position

**Source size** < 0.7 pc

Bursts coincident within $2\sigma$: < 40 pc at 95% C.L.

Marcote et al. (2017, ApJL, 834, 8)
The optical counterpart

- Archival Keck data from 2014
- Gemini observation (Oct 2016)
- HST data in early 2017
- Extended 25-mag counterpart
- \( z = 0.19273(8) \rightarrow 972 \text{ Mpc} \)

- **Dwarf galaxy:**
  - Diameter: \( \lesssim 5\text{–}7 \text{ kpc} \)
  - Mass: \( 10^8 \text{ M}_\odot \)
  - Star Formation: \( \sim 0.4 \text{ M}_\odot \text{ yr}^{-1} \)

- **Low-metallicity star-forming region:**
  - Diameter of \( \sim 1.3 \text{ kpc} \)

Observations at 5 GHz

Arecibo and Green Bank telescopes

Bursts $\sim 100\%$ linearly polarized

High Faraday rotation measure:
$\approx 1.4 \times 10^5 \text{ rad m}^{-2}$

Discussion & Conclusions
Summary from FRB 121102

- FRB 121102 is associated with a compact source located in the star-forming region of a dwarf galaxy

- **Are FRBs located in dwarf galaxies?**
  - Is FRB 121102 an exception?
  - Are there more repeating FRBs?

- Localization of more FRBs is still needed, but this do not guarantee the unveiling of its nature

- Burst emission at other wavelengths?

- Still no clear scenario to explain FRB 121102…
- Young superluminous supernovae powered by the spin-down power of a neutron star or magnetar (e.g. Murase et al., Piro et al. 2016)

- Neutron star interacting with the jet of a massive black hole ($\sim 10^{5-6} \, M_\odot$) (Pen & Connor 2015, Cordes & Wasserman 2016, Zhang 2018)

- Bursts produced by a strong plasma turbulence excited by the jet of a massive black hole (Romero et al. 2016, Vieyro et al. 2017)

- Synchrotron maser activity? (Ghisellini 2017)

- ...
The future for Fast Radio Bursts

- More precise localizations are required in this field

- Discoveries of new repeaters?

- Several instruments with time dedicated to discover new FRBs: UTMOST, Apertif, CHIME, ASKAP,…

- Some of them will produce arcsecond localizations

- Detection of bursts on mas scales are required to pinpoint associated counterparts
RadioNet has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 730562.
Observations at other wavelengths

**Bursts at other wavelengths:**

- Optical upper-limits on burst fluence of $< 0.046$ Jy ms (Hardy et al. 2017)
- Optical/TeV-radio observations with MAGIC: (MAGIC Coll. et al. 2018)

**Concerning the persistent counterpart:**

- GeV: No significant *Fermi*/LAT emission: $\lesssim 4 \times 10^{44}$ erg s$^{-1}$
Next step: find counterparts (higher resolution)

The main problem with FRBs is the lack of known counterparts

- We only have tentative distances (DM)
- Precision of several arcmin
- Hundreds/thousands of possible counterparts
The repeater FRB 121102 (Spitler et al. 2016, Nature, 531, 202)

Among bursts. We therefore conclude that the spectral shapes and variations are likely to be predominantly intrinsic to the source. An analysis of the arrival times of the bursts did not reveal any statistically significant periodicity (see Methods). If the source has a long period ($\geq 1$ s), then it is probably emitting at a wide range of rotational phases, which is not uncommon for magnetars, making a convincing period determination difficult. Owing to the small number of detected bursts, we are not sensitive to periodicities much shorter than $\sim 100$ ms.

Repeat bursts rule out models involving cataclysmic events—such as merging neutron stars or collapsing super-massive neutron stars. Bursts from Galactic flare stars have been proposed as a model for FRBs with the DM excess originating in the stellar corona. However, temporal density variations in the corona should produce bursts with varying DMs, which we do not observe. Planets orbiting in a magnetized pulsar wind may produce a millisecond-duration burst once per orbital period; however, the observed intra-session separations of our bursts (23–572 s) are too short to correspond to orbital periods. Repeated powerful radiative bursts are associated with magnetars, and indeed, giant flares from the latter have been suggested as a FRB source. However, no Galactic magnetar has been seen to emit more than a single giant flare in over four decades of monitoring, arguing against a magnetar giant flare origin for FRB 121102. Magnetars have 1,250, 1,300, 1,350, 1,400, 1,450, 1,500 MHz Observation frequency (MHz).
Next step: find counterparts

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- We only have a tentative distance
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The repeater FRB 121102

- The bursts seem to be localized in freq.
- Width of hundreds of MHz
- Rate vs $E$: power-law
- Different normalization depending on the “epoch”

The VLA localization of FRB 121102

SED and radio spectrum of FRB 121102

(Chatterjee et al. 2017, Nature, 541, 58)
The optical counterpart

The optical counterpart

BPT diagrams

Emission lines dominated by Star Formation

No emission detected at:

- sub-mm (ALMA) rms of 17 µJy
- X-rays (Chandra, XMM) $< 5 \times 10^{41} \text{ erg s}^{-1} (5\sigma)$
- $\gamma$-rays (Fermi/LAT)
Simultaneous radio and X-ray observations

- 12 radio bursts observed

- No X-ray photons at those times
  \( < 3 \times 10^{-11} \text{ erg cm}^{-2} \)
  or \( \sim 4 \times 10^{45} \text{ erg} \)

- No X-ray bursts at all
  \( < 5 \times 10^{-10} \text{ erg cm}^{-2} \)

- No *Fermi*/GBT detections:
  \( < 4 \times 10^{-9} \text{ erg cm}^{-2} \)

- X-ray Persistent emission?
  \( L < 3 \times 10^{41} \text{ erg s}^{-1} \)

The radio counterpart

- Bursts and persistent radio source coincident within 40 pc

- Compactness at 5 GHz $\Rightarrow$ source $\lesssim 0.7$ pc

- No afterglows observed

- Extragalactic origin also supported by the EVN radio observations: Scintillation & scatter broadening

- Offset from the center of the host galaxy, within the star-forming region

- Brightness temperature $T_b \gtrsim 5 \times 10^7$ K
Polarization and Faraday Rotation Measure

Observations at 5 GHz

Arecibo and Green Bank telescopes

Bursts \( \sim 100\% \) linearly polarized

High Faraday rotation measure:
\( \approx 1.4 \times 10^5 \ \text{rad m}^{-2} \)

Polarization and Faraday Rotation Measure

Possible origins for FRB 121102 (facts)

- The star-forming region in the dwarf galaxy resembles the hosts of long-duration gamma-ray bursts and hydrogen-poor superluminous supernovae

- The persistent source is more consistent with a low-luminosity massive black hole

- This high rotation measure has only been observed in pulsars/magnetars around Sgr A* (a $10^6$-$M_\odot$ black hole)

- Structures observed in the bursts similar to other FRBs or the giant Crab flares
No periodicities are observed at all.

Bursts exhibit short bandwidths (\( \sim 500 \) MHz)

Shortest separation between bursts: \( \sim 34 \) and 37 ms
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FRB 110220 and FRB 140514 were detected within 9 arcmin and 3-yr apart.

- FRB 110220. DM = 944.4 pc cm$^{-3}$ (Thornton et al. 2013)
- FRB 140514. DM = 562.7 pc cm$^{-3}$ (Petroff et al. 2015)

Probability of chance coincidence: 1–32%

Possible explanations: DM dominated by SNR (young and expanding) (Piro & Burke-Spolaor 2017)
Swift detected a 100-s transient coincident with FRB 131104 (DeLaunay et al. 2016)

- 15–200 keV
- $E \sim 5 \times 10^{51}$ erg

However,

- 3-σ detection
- Change coincidence subestimated (Shannon & Ravi 2017)

- Would point out to a much different (and close) distance (Gal & Zhang 2017)
FRB 150418: The first announced association

Keane et al. (2016, Nature, 530, 453)

Parkes detection
ATCA follow-up 2-hr later.

Association with a transient source
Early-type galaxy at $z \sim 0.5$

...or just an unassociated AGN?
Williams & Berger (2016)
Vedanthan et al. (2016)
Giroletti et al. (2016)
Bassa et al. (2016)