Preparing for the Unexpected

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Computing for SKA Colloquium
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Outline

• Recent Example
  – Fast Radio Bursts and transient buffers

• Two Predictions
  – cyclic spectroscopy
  – periodic correlation (fourth-order moments)
A Population of Fast Radio Bursts at Cosmological Distances

D. Thornton,1,2* B. Stappers,1 M. Bailes,3,4 B. Barsdell,3,4 S. Bates,5 N. D. R. Bhat,3,4,6 M. Burgay,7 S. Burke-Spolaor,8 D. J. Champion,9 P. Coster,2,3 N. D’Amico,10,7 A. Jameson,3,4 S. Johnston,2 M. Keith,2 M. Kramer,9,1 L. Levin,5 S. Milia,7 C. Ng,9 A. Possenti,7 W. van Straten3,4

Searches for transient astrophysical sources often reveal unexpected classes of objects that are useful physical laboratories. In a recent survey for pulsars and fast transients, we have uncovered four millisecond-duration radio transients all more than 40° from the Galactic plane. The bursts’ properties indicate that they are of celestial rather than terrestrial origin. Host galaxy and intergalactic medium models suggest that they have cosmological redshifts of 0.5 to 1 and distances of up to 3 gigaparsecs. No temporally coincident x- or gamma-ray signature was identified in association with the bursts. Characterization of the source population and identification of host galaxies offers an opportunity to determine the baryonic content of the universe.

The four fast radio bursts (FRBs) (Fig. 1) reported here were detected in the high Galactic latitude region of the High Time Resolution Universe (HTRU) survey (1), which was designed to detect short-time-scale radio transients and pulsars (Galactic pulsed radio sources). The survey uses the 64-m Parkes radio telescope and its 13-beam receiver to acquire data across a bandwidth of 400 MHz centered at 1.382 GHz (table S1). We measured minimum fluences for the FRBs of $F = 0.6$ to 8.0 Jy ms (1 Jy = $10^{-26}$ W m$^{-2}$ Hz$^{-1}$) (2). At cosmological distances, this indicates that they are more luminous than bursts from any known transient radio source (3). Follow-up observations at the original beam positions have not detected any repeat events, indicating that the FRBs are likely cataclysmic in nature.

Candidate extragalactic bursts have previously been reported with varying degrees of plausibility (4–7), along with a suggestion that FRB 010724 (the “Lorimer burst”) is similar to other signals that may be of local origin (8, 9). To be consistent with a celestial origin, FRBs should exhibit certain pulse properties. In particular, observations of radio pulsars in the Milky Way (MW) have confirmed that radio emission is delayed by propagation through the ionized interstellar medium (ISM), which can be considered a cold plasma. This delay has a power law dependence of $\delta t \propto DM^{-1/2}$ and a typical frequency-dependent width of $W \propto v^{-4}$. The dispersion measure (DM) is related to the integrated column density of free electrons along the line of sight to the source and is a proxy for distance. The frequency-dependent pulse broadening occurs as an astrophysical pulse is scattered by an inhomogeneous turbulent medium, causing a characteristic exponential tail. Parameterizing the frequency dependence of $\delta t$ and $W$ as $\alpha$ and $\beta$, respectively, we measured $\alpha = -2.003 \pm 0.006$ and $\beta = -4.0 \pm 0.4$ for FRB 110220 (Table 1 and Fig. 2), as expected for propagation through a cold plasma. Although FRB 110703 shows no evidence of scattering, we determined $\alpha = -2.000 \pm 0.006$. The other FRBs do not have sufficient evidence of scattering, we determined $\alpha = -2.000 \pm 0.006$.
The position given is the center of the gain pattern of the beam, aligned to time = 0. The data are shown as solid gray lines and the best-fit profiles by dashed black lines. The energy released is calculated from the average peak fluence at 1.3 GHz, given a small scale-height error; where fitted, energy \( E \) is associated with any FRBs. In particular there is no energy inferred associated with FRB 010724, however, observations have not detected any gravitational wave triggers that can be temporally correlated with FRB 010724.

The energy of the critical density of matter \( \rho_c \) is characterized by bright bands ~100 MHz wide (Fig. 2); the SNRs are too low in the other three wide dedispersed subbands used. No excess-DM FRBs were detected in the PMPS surveys \( \text{(PMPS)} \) surveys \( \text{b} \) and \( \text{c} \). Similar spectral characteristics are commonly observed in the energy distribution across the band in FRB 110220.

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Identifying the source of perytons at the Parkes radio telescope


Abstract

‘Perytons’ are millisecond-duration transients of terrestrial origin, whose frequency-swept emission mimics the dispersion of an astrophysical pulse that has propagated through tenuous cold plasma. In fact, their similarity to FRB 010724 had previously cast a shadow over the interpretation of ‘fast radio bursts’ (FRBs), which otherwise appear to be of extragalactic origin. Until now, the physical origin of the dispersion-mimicking perytons had remained a mystery. We have identified strong out-of-band emission at 2.3–2.5 GHz associated with several peryton events. Subsequent tests revealed that a peryton can be generated at 1.4 GHz when a microwave oven door is opened prematurely and the telescope is at an appropriate relative angle. Radio emission escaping from microwave ovens during the magnetron shut-down phase neatly explains all of the observed properties of the peryton signals. Now that the peryton source has been identified, we furthermore demonstrate that the microwave ovens on site could not have caused FRB 010724. This and other distinct observational differences down phase neatly explain all of the observed properties of the peryton signals. Now that the peryton source has been identified, we furthermore demonstrate that the microwave ovens on site could not have caused FRB 010724. This and other distinct observational differences.
A Christmas Gift for Physicists: The Fixion

A new particle that explains everything

- Main component of dark matter
- Neutralizes monopoles
- Spontaneously emits dark energy
- Introduces dispersion into perytons from kitchen microwaves, explaining fast radio bursts
- Causes alpha effect, intercepts certain gravitational waves before they're observed
- Higgs-ish
- Accelerates certain spacecraft during flybys
- Melts ice in "snowball Earth" scenario
- Suppresses sigma in experiments
- Confines quarks and gluons
- Suppresses antimatter in early universe
- Mediates proton decay but then hides it
- Broken symmetry causes θ=0, explaining unobserved neutron dipole moment
- Covers naked singularities
- Causes coronal heating
- Superluminally smooths anisotropies in early universe (but adds faint polarization for BICEP3 to find)
- Triggers Siberian sinkholes
- Transports neutrinos faster than light, but only on certain days through one area of France.
A direct localization of a fast radio burst and its host


Fast radio bursts are astronomical radio flashes of unknown physical nature with durations of milliseconds. Their dispersive arrival times suggest an extragalactic origin and imply radio luminosities that are orders of magnitude larger than those of all known short-duration radio transients. So far all fast radio bursts have been detected with large single-dish telescopes with arcminute localizations, and attempts to identify their counterparts (source or host galaxy) have relied on the contemporaneous variability of field sources or the presence of peculiar field stars or galaxies.

These bursts were initially detected with real-time de-dispersed imaging and confirmed by a beam-formed search (Fig. 1). From these detections, the average J2000 position of the burst source is right ascension $\alpha = 05 h 31 m 58.70 s$, declination $\delta = +33^\circ 08' 52.5''$, with a 1σ uncertainty of around 0.1″, consistent with the Arecibo localization but with three orders of magnitude better precision. The dispersion measure (DM) for each burst is consistent with the previously reported value of $558.1 \pm 3.3$ pc cm$^{-3}$, with comparable uncertainties. Three bursts detected at the VLA (2.5–3.5 GHz) had simultaneous coverage...
The simplest interpretation is that the burst source resides in a host halo, given the DM values and redshift constraints. The host halo is likely a dwarf galaxy, as indicated by the low star-formation rate and luminosity distances.

The spectrum of the persistent source shows complex features, including broad lines and a strong X-ray component. This suggests the presence of a central engine, such as an AGN, which could be powering the radio emissions and the optical counterpart.

The compactness of the persistent radio source, less than about 8 arcsec, indicates a compact source or a highly collimated beam. The projected separation of the burst source and the persistent source is also consistent with a compact association.

The spectral energy distribution (SED) of the source is consistent with a supermassive black hole (SMBH) accreting material from a circumnuclear disk. The strength of the optical emission suggests a high accretion rate, which is supported by the X-ray observations.

In summary, the burst source and the persistent source are likely associated with a dwarf galaxy hosting an AGN. The low star-formation rate and the compact radio source support this interpretation, and further observations are needed to confirm the nature of the host galaxy and the mechanism of the burst.
The global missing baryon problem

- Ly α
- WHIM
- ICM
- CGM
- HI
- stars
- missing

~30% of the baryons expected from BBN have yet to be detected (Shull et al. 2012)
Prediction 1:
Multipath propagation
Lazio et al. (2004)
Cyclic Spectroscopy

\[ S_x(\nu; \alpha) = E \{ X(\nu + \alpha/2)X^*(\nu - \alpha/2) \} \]

- \( \alpha = k/P = \) harmonics of spin frequency
- \( \nu = \) radio frequency
- \( X(\nu+\alpha/2) = \) RF spectrum “mixed” with harmonic of spin frequency
- upper and lower “sidebands” cross-multiplied
Adaptive Optics for Pulsars

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<tr>
<th>Cyclic spectrum</th>
<th>SKA1-Low</th>
<th>SKA1-Mid B1</th>
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<tr>
<td>Bandwidth (MHz)</td>
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<td># phase bins</td>
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<td>TMACs</td>
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<td>Input Res. (kHz)</td>
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<td>49</td>
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<tr>
<td>Output Res. (MHz)</td>
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<tr>
<td>Max DM</td>
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<td>3000</td>
<td>3000</td>
</tr>
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12.5 X!
Prediction 2: Pulsar Intrinsic Fluctuations
SWIMS:
Stochastic Wideband Impulse Modulated Self-noise

Oslowski et al. (2011)
Template Matching

\[ \chi^2 = \Sigma \left[ P(\phi) - aS(\phi + \varphi) + b \right]^2 \]
Ordinary Least Squares

- Homoscedastic
- Uncorrelated
Ordinary Least Squares

- Homoscedastic – flux heavily modulated
- Uncorrelated
Ordinary Least Squares

- Homoscedastic – flux heavily modulated
- Uncorrelated – temporal/spectral structure
Ordinary Least Squares

- **Homoscedastic** – flux heavily modulated
- **Uncorrelated** – temporal/spectral structure

- Bias Correction (Osłowski et al. 2011)
  - Principal Component Analysis
  - Multiple Regression Analysis

- Better Error Bars (Shannon et al. 2014)
  - 7 / 22 PPTA MSPs
Generalized Least Squares

• Unbiased \textbf{and} better error bars

\[ \chi^2 = (D - M)^T C^{-1} (D - M) \]

• \( C = \) covariance matrix of fluctuations

• \( C \) is unknown
  – cannot be estimated from data, \( D \)
  – cannot be estimated from residuals, \( D - M \)
Feasible Generalized Least Squares

• model $C$ with some parameters $\theta_i$

• Simultaneously derive $\theta_i$ and desired phase shift $\varphi$ during model fit

• $C$ includes SEFD and PSR terms

• Covariances between intensities are fourth moments of the electric field
## Higher Moments for Pulsars

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<td>1024</td>
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<tr>
<td># polarizations</td>
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<td>4</td>
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<tr>
<td>Pulsar period (ms)</td>
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<td>1</td>
</tr>
<tr>
<td>GMACs</td>
<td>250</td>
<td>590</td>
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Square Kilometre Array

• Computing the cyclic spectrum
  – computationally prohibitive
  – SKA1-Low: divide band over 16 node

• Computing fourth moments
  – computationally feasible
  – uncertain if it helps FGLS
Directions

• Cyclic Spectroscopy
  – interstellar delay monitor for PTAs
  – ~ AU structure of magnetoionic ISM

• Feasible Generalized Least Squares
  – beat down white noise in PTAs
  – characterize pulsar emission mechanism
Thank you!