Surveys of Substructure in Pulsar Glitch Populations

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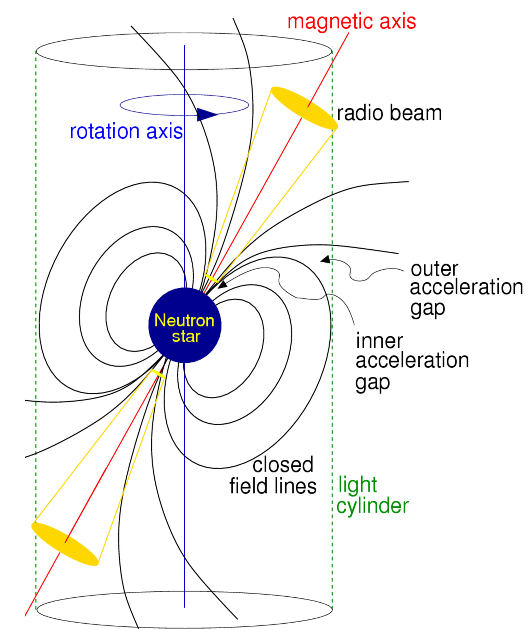
Pulsars and Pulsar Timing

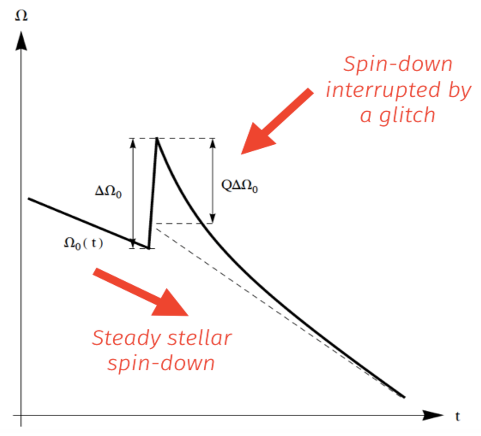
- Pulsars are **rotating neutron stars**
- **Strong magnetic fields** (~10^{12} Gauss from dynamo effect). misaligned with rotation axes
- Characterized by misalignment between rotation and magnetosphere axes
  - **Coherent radio emission** in a conical beam
  - Observed as pulses when beam sweeps across line of sight, similar to a **lighthouse**



Canonical pulsar magnetosphere (Image by NRAO/Scott Ransom)

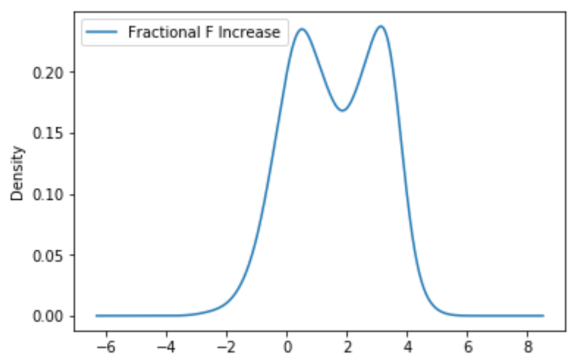
- Rotation is stable due to their extremely high moment of inertia and relative isolation
- Pulse **time of arrivals (TOAs)** are measured precisely to produce timing observations
  - Each "pulse" corresponds to a spin period
- TOAs are generally fitted with a third degree Taylor polynomial—a **pulsar timing solution**

- **Rotation anomalies:** glitches and timing noise
- **Glitches:** discontinuous spin-up events
  - First glitch discovered in Vela (J0835-4510)
- **Timing Noise:** stochastic, random variations in timing residuals
  - Sometimes quasi-periodic; highly varied



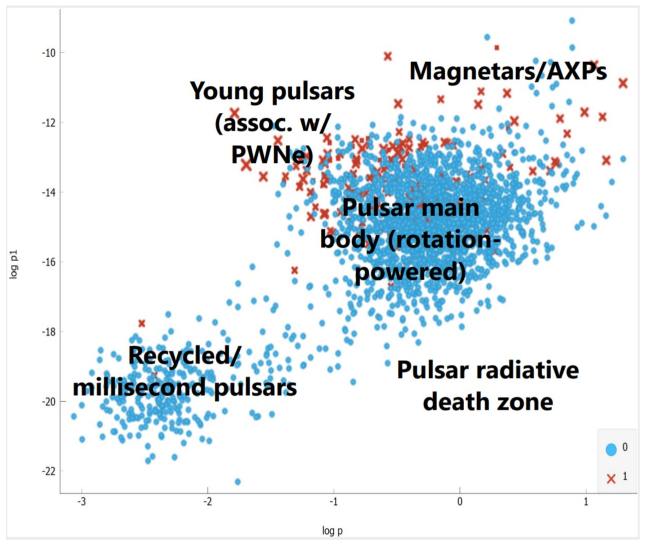
Pulsar glitch diagram including exponential recovery (Astrobites)

Glitch Data



KDE plot of fractional glitch step size

- **500+ glitches** in **180+ pulsars**
- Parameters (size, epoch, recovery) measured with increasing precision
- Direct probes of neutron star interiors
  - True mechanism is elusive



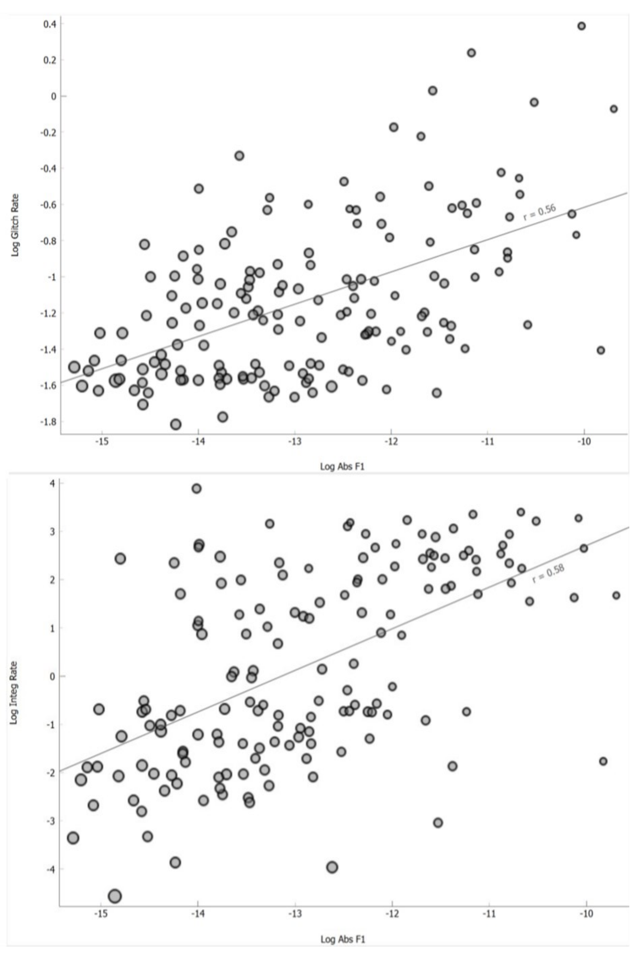
Canonical P-Pdot diagram; **glitching pulsars in red**

- Full glitch database compiled comparing independent reports, databases, and calculated additional glitch features
  - 555 glitches in total
- Glitching pulsar database compiled & combined with ATNF pulsar database
  - 187 glitching, 2620 non-glitching

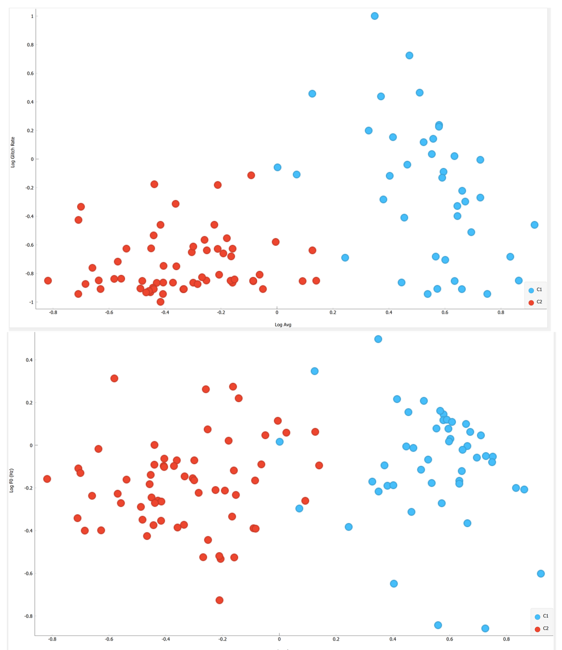
- Gaussian Kernel Density Estimation (KDE) used to confirm **bimodality of fractional glitch size** (dF/F), as noted by Espinoza et al. (2011)
  - Independent of histogram binning
  - Fractional frequency derivative size (dF1/F1) **also slightly bimodal**

- Roughly match **canonical pulsar distributions** on pulsar period-period derivative (P-Pdot) diagram

- Espinoza et al. (2011) observe linear relationships between spin-down rate (F1) and glitch rate (integrated spin-up and individual events)
- Confirmed & highly significant with expanded dataset

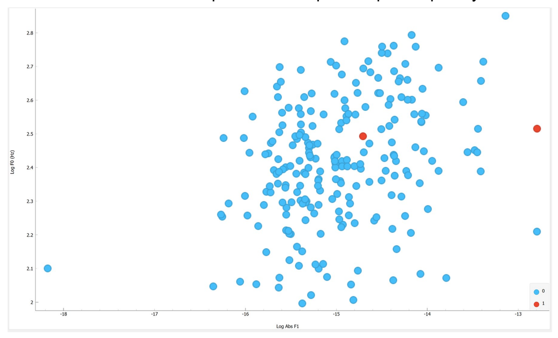

Top: glitch rate (# events/year) vs. frequency derivative
Bottom: glitch rate (integrated spin-up/year) vs. frequency derivative

Glitching Pulsars


Top: apparent underdensity in medium glitches
Bottom: no dependence on pulsar spin frequency

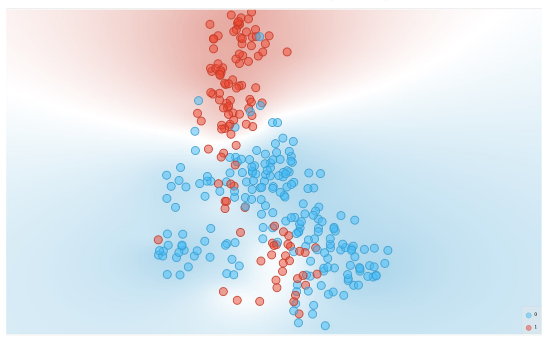
Cluster Analysis

- Distribution of glitching pulsars tends to follow standard pulsar distribution
- Underdensity between pulsars experiencing larger and smaller glitches
- Pulsars experiencing larger glitches experience a wide range of glitch rates
- Pulsars experiencing smaller glitches tend to glitch at lower overall rates
- No dependence on spin frequency
- Suggests minimum size for some pulsars


Millisecond pulsar population; glitching in red

Millisecond Pulsars:

- Glitching pulsar J1824-2452A appears to be a strong outlier (DBSCAN)
- J0613-0200 is well-embedded in main body of MSPs


Classification results projected in 2D; glitching in red

Classification Results:

- Do all pulsars glitch?
- Glitching vs. non-glitching pulsars are **significantly different**, but subject to Poisson statistics & observational effects
- Build classifiers to understand populations
  - Age is the strongest factor

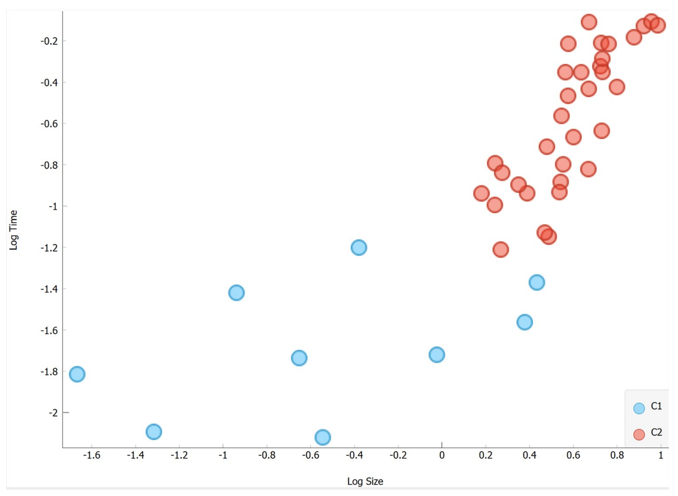
Behavior of Prolific Pulsars

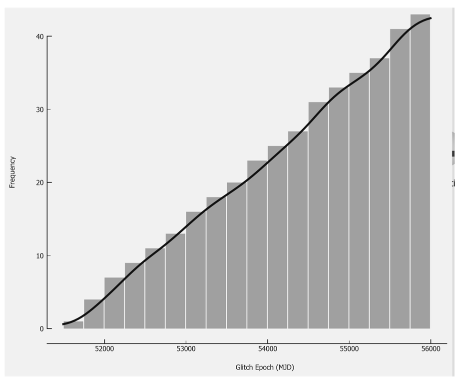
J0534+2200 (Crab)	30
J0537-6910	45
J0631+1036	17

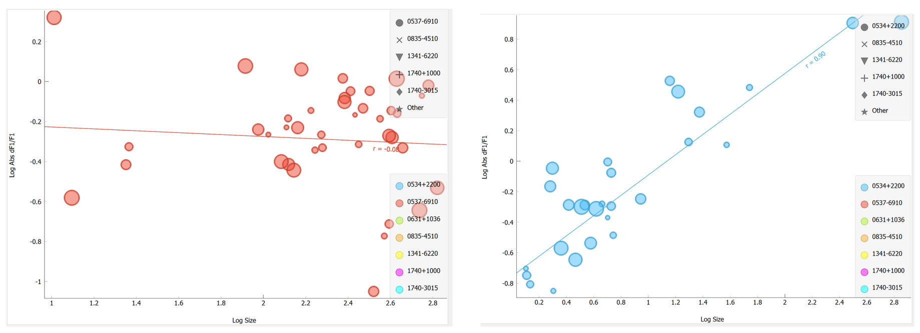
J0835-4510 (Vela)	20
J1341-6220	23
J1740-3015	36

- Prolific pulsars: >15 glitches
- **Main takeaways:**
  - J0537-6910 and J0835-4510 exhibit clusters of glitches with distinctly different behavior
  - Prolific pulsars fall are either **Crab-like** or **Vela-like**

- No clustering within full population or J0534+2200, J0631+1036, J1341-6220, J1740-3015
- J0537-6910 exhibits strong clustering
  - Main, dense group of glitches at similar sizes & waiting times
  - Outlying smaller group
- Produces bimodal size distribution
- Similar behavior in J0835-4510


Apparent clusters in J05376-6910


Cumulative waiting time dist. for J05376-6910


Right: dF1/F1 vs. dF/F for J0537-6910 (Vela-like)
Left: dF1/F1 vs. dF/F for J0835-6910 (Crab)

VELA-LIKE PULSARS:

- Quasi-periodic behavior; near-linear cumulative waiting time distributions
- No relationship with dF/F & dF1/F1
- Strong forward waiting time dependence

- Clusters in J0537-6910 and J0835-4510 show **markedly different statistical behavior**
- Match either Crab-like or Vela-like

CRAB-LIKE PULSARS:

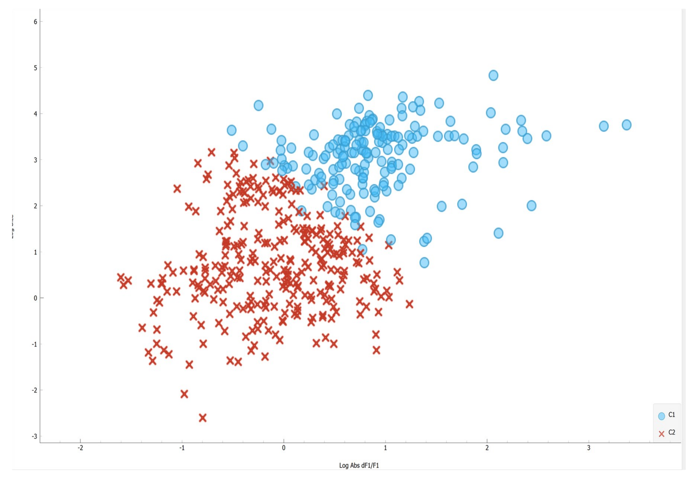
- Strong relationship between dF/F & dF1/F1
- Exponential waiting time & power-law size
- No waiting time dependence

Relationship	J0537-6910 Main Cluster	J0537-6910 Outlying Cluster	J0835-4510 Main Cluster	J0835-4510 Main Cluster
dF/F vs. dF1/F1	NO	YES: R=0.85	NO	YES: R=0.54
Waiting Time to Next Glitch vs. dF/F	YES: R=0.92	NO	YES: R=0.66	NO

The Full Glitch Population

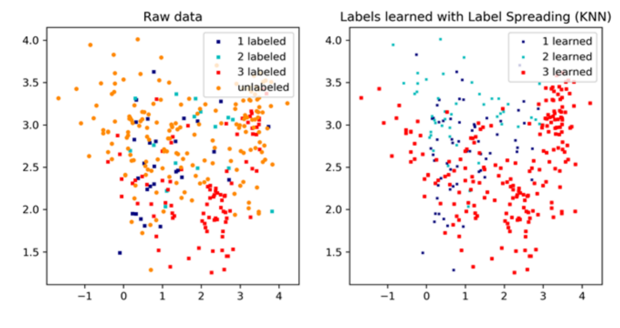
Main Takeaway:

- There is no strong clustering or separation within the entire pulsar glitch population (555 glitches)
- Necessitates considering glitch phenomenology primarily within individual pulsars
- Bimodal dF/F and dF1/F1, but no strong clusters visible with these features


Clustered plot of dF/F vs. dF1/F1, n=2

Clustering Approaches:

- Semi-supervised learning with Lyne et al. 2004's heuristic classes
- Cluster analysis of full population glitch parameters (derived)
- Cluster analysis of raw residuals w/ dimensionality reduction



Semi-supervised learning experiment; classes appear poorly separated

Discussion & Physical Models

- Superfluid vortices to pin to ions in the lattice or to magnetic flux tubes
- Pinned superfluid decouples from the crust
  - Reservoir of angular momentum released by a **trigger mechanism**

Starquakes: crust breaks locally once a *critical strain* is reached

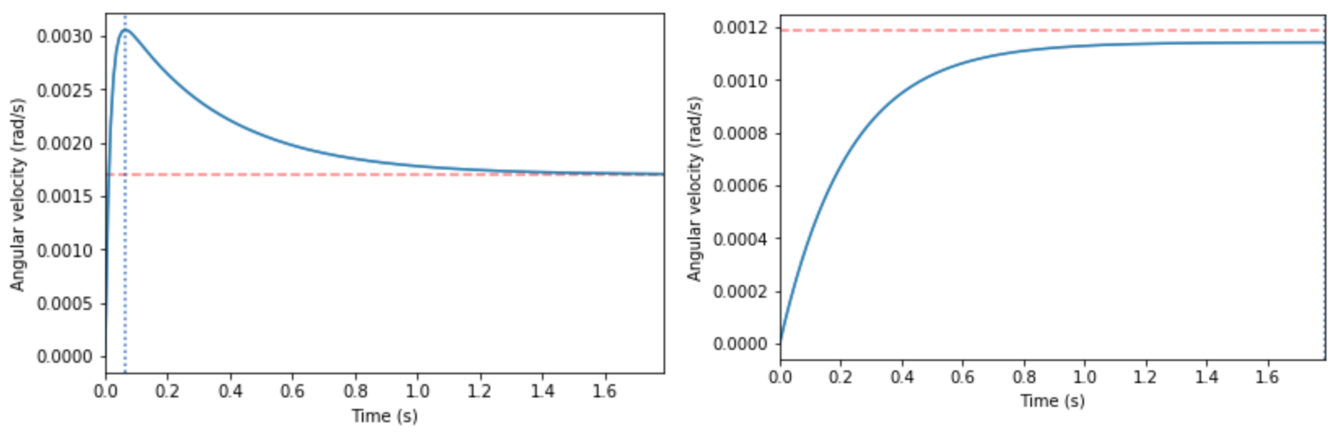
"Snowplow" Model: reaching a maximum lag causes *global unpinning*

Vortex Avalanches: random local variations cause *regional unpinning*

What physics can we get from glitch statistics?

- J0534+2200, J0631+1036, J1740-3015: avalanches/starquakes
  - Spikes in glitch rate slightly above the smallest scales
  - Scale-invariant statistics & no waiting time dependency
- J0537-6910, J0835-4510, J1341-6220: snowplow model
  - Quasi-periodic behavior and forward waiting time dependency
  - Avalanches with a constrained size may quasi-periodic
- Multiple glitch mechanisms and triggers may exist within a pulsar
  - Clusters of glitches J0537-6910 and J0835-4510.
  - Exhibit different characteristics aligned with physical models

- Observations in high cadence (Ashton et al. 2019) constrain **rise times**
- New models (Pizzochero et al. 2020) show detail in early behavior
- Substructure to explore:
  - Multi-wavelength/polarized radiative counterparts to glitches
  - Anti-glitches & micro-glitches



Sample complex rises simulated using a three-component model

Acknowledgements

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