**Pulsars and Pulsar Timing**

- Pulsars are rotating neutron stars
- Strong magnetic fields (~10¹⁵ 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
- 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

**Timing Anomalies**

- 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

**Glitch Data**

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

**Behavior of Prolific Pulsars**

- 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

**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**

- 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

**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

**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

### 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

**Glitches**

- 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

**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

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