Neutron star spin wandering:

Consequences and implications

Andrés F. Vargas Sánchez

On behalf of the University of Melbourne

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ARC Centre of Excellence for Gravitational Wave Discovery

The University of Melbourne

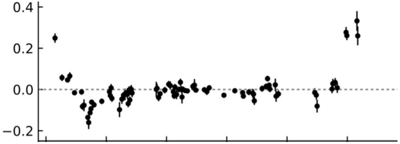
Overview:

The pulse phase series is decomposed as:

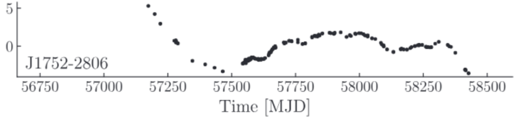
$$\phi(t) = \phi_0 + \nu(t - t_0) + \frac{1}{2}\dot{\nu}(t - t_0)^2 + (\text{other terms}) + \delta\phi(t)$$

Spin wandering:

Time-correlated stochastic structures in the pulse arrival times not associated to measurement error. Could arise due to internal (e.g. crust-superfluid coupling) or external (e.g. accretion) mechanisms.



Phase residuals (units: cycles) of an accreting millisecond X-ray pulsar. From: Bult. P *et al.* (2022).



timing residuals (below; units: ms) of an isolated pulsar. From: Lower. M. E. *et al.* (2020).

Implications

CWs

CW detection with hidden Markov model (HMM; see later) + EM ephemeris

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Crust-quadrupole lag

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Superfluidity

Glitches

Disentangling spin wandering and glitches systematically with hidden Markov model

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Better glitch statistics

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Nuclear pinning

Secular braking

Disentangling spin wandering and secular braking

↓

Torque physics (EM, GW, magnetic field decay, etc.)

The HMM pipeline

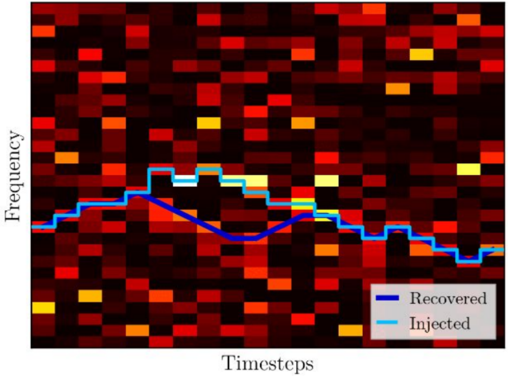
The pipeline involves:

(a) Hidden parameters $\rightarrow$ GW frequency $f(t)$

(b) Observable states $\rightarrow$ Detector data

(c) Statistic $\rightarrow$ $L[f(t)|\,\text{Detector data}\,]$

- $f(t)$ is allowed to jump by -1, 0, +1 frequency bins at every step of T_{drift}.
- The Viterbi algorithm tracks $f(t)$.



HMM tracking. Image made by J. Carlin. and H. Middleton.

Searches using the HMM pipeline

Key contributor for LIGO:

- six searches using O3 data
- at least three planned searches using O4 data.

In the absence of a detection, the main results are upper limits on the GW strain h_0.

PHYSICAL REVIEW D **105,** 022002 (2022)

Search for continuous gravitational waves from 20 accreting millisecond x-ray pulsars in O3 LIGO data

R. Abbott *et al.*[*]
(LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration)

$$h_0 \geq 4.7 \times 10^{-26}$$

PHYSICAL REVIEW D **106,** 062002 (2022)

Search for gravitational waves from Scorpius X-1 with a hidden Markov model in O3 LIGO data

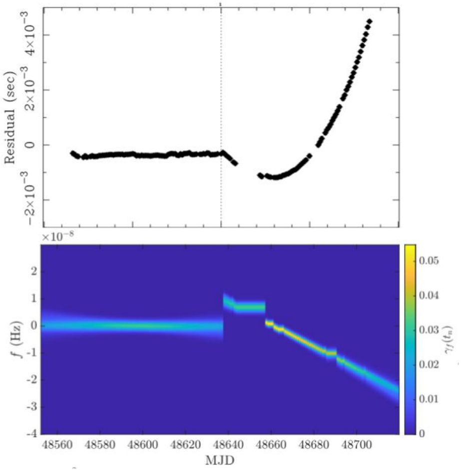
R. Abbott *et al.*[*]
(LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration)

$$h_0 \geq 6.2 \times 10^{-26} \quad (\iota = 44^\circ)$$

Some searches using the HMM pipeline.

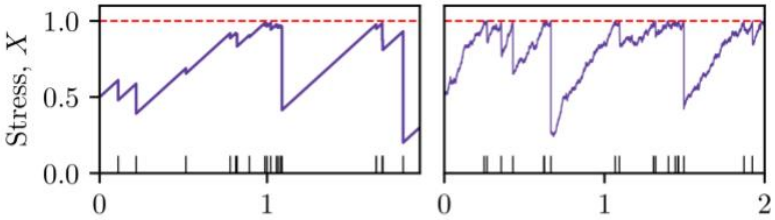
Disentangling spin wandering from glitches

- Glitches: impulsive, erratically occurring, spin-up events.
- Glitches probe bulk matter at nuclear densities.
- Studying them is complicated by spin wandering before and after the glitch.
- A HMM can be used to disentangle spin wandering from glitches.



Glitch (above) and HMM tracking (below). From: **Dunn. L. et al. (2023)**

Glitch statistics



Stress time series for two meta models: state dependent Poisson (left), and Brownian (right).
Note: The linear ramp (left) approaches the threshold, while the Brownian ramp (right) reaches it.

- Size and waiting time PDF, cross-correlation, and autocorrelation can distinguish between meta models.
- The Brownian meta-model is ruled out by six pulsars with ≥ 10 glitches. See: Carlin. J. B., and Melatos. A. (2019), (2020), and (2021).

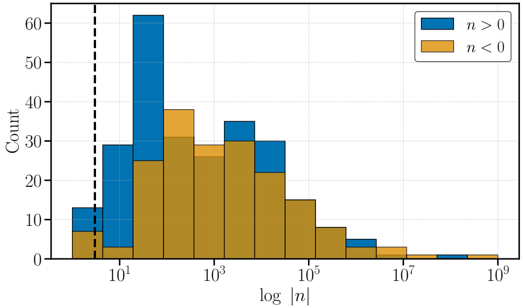
Disentangling pulsar's secular spin down from spin wandering

- NS are believed to spin down following

$$\dot{\nu} = K\nu^{n_{\rm pl}}.$$

- Is it $n_{\rm pl} \approx 3$? or maybe $n_{\rm pl} \approx 5$? Does K evolve, e.g. magnetic field decay?

- Yet, timing experiments yield $3 \ll |n| \lesssim 10^6$ for some pulsars. We call these anomalous braking indices.



Distribution of $n = \nu\dot{\nu}/\dot{\nu}^2$, taken from the ATNF pulsar catalogue.

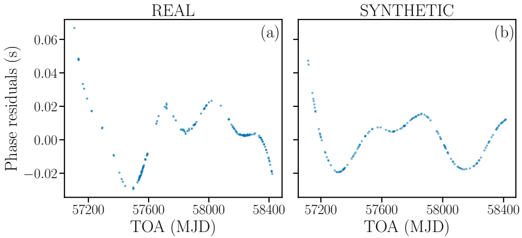
Could spin wandering be behind this? — Yes!

Quantifying the effect of timing noise in measurements of n

- Idealized phenomenological model: The NS rotational parameters execute a mean-reverting, random walk driven by $\xi(t)$.

- $\xi(t)$ is a fluctuating, zero-mean, Langeving driver satisfying

$$\langle \xi(t)\xi(t') \rangle = \sigma_{\ddot{\nu}}^2 \delta(t - t'). \quad (1)$$



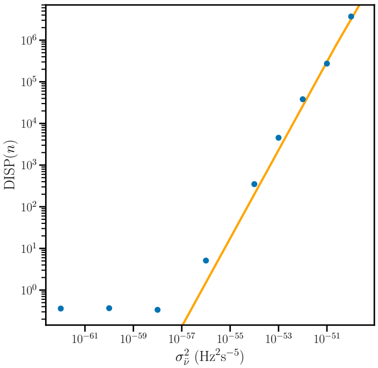
Actual (left) and synthetic (right) phase residuals.
From: Vargas. A. F. and Melatos A. (2023)

Results: Variance of n

A predictive, falsifiable formula for the variance of the measured n, viz.

$$\langle n^2 \rangle = {n_{\rm pl}}^2 + \frac{{\sigma_{\ddot{\nu}}}^2 \nu^2}{{\gamma_{\ddot{\nu}}}^2 \dot{\nu}^4 T_{\rm obs}}, \qquad (2)$$

- $\sigma_{\ddot{\nu}}/\gamma_{\ddot{\nu}}$ depends on nuclear properties, e.g. crust-superfluid coupling time-scale.
- Can modify for $K \neq$ constant! Vargas. A. F. and Melatos A. (2024).



Variance of n versus $\sigma_{\ddot{\nu}}^2$. From: Vargas. A. F. and Melatos A. (2023)

Summary

Takeaway points

- A pulsar's spin frequency wanders stochastically with time due to internal or external mechanisms.
- Spin wandering complicates CW searches, glitch detections, and measuring NS spin down.
- Yet, accommodating for it, has important implications for superfluidity, nuclear pinning, and NS's braking mechanisms, among others.
- Extensions to the ideas and methods here presented can be applied to produce:
  - new GW detection algorithm for pulsar timing arrays. See Kimpson. T. *et al.* (2024a) and (2024b).
  - A Bayesian scheme to infer $n_{\rm pl}$ and $\sigma_{\ddot{\nu}}/\gamma_{\ddot{\nu}}$ for pulsar populations.

Backup slides

The University of Melbourne CW/NS group

- The group consists of ≥ 20 members all supervised by Dr. Andrew Melatos (who sends his regards).

The venerable.

- The group works on a broad range of topics. For CWs and spin wandering, it contributions are divided between theory and data analysis.

The group.

The University of Melbourne CW program

Theory:

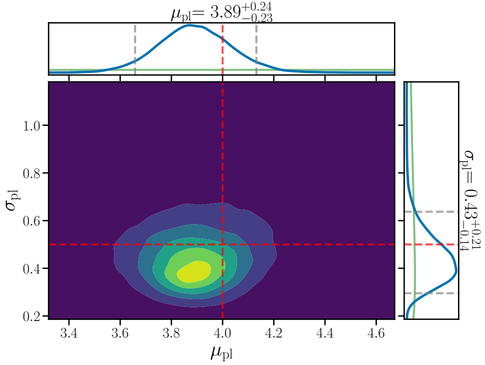
- **CW emission:** Mountains **(R. Brunet. Former: A. Kerin, and P. Rossetto)** , oscillations modes due accretion **(E. Dong)** , and pinned superfluid vortices **(J. Thong, and T. Cheunchitra. Former: J. Carlin, and G. Howitt)** .
- **Glitch statistics** **(Former: J. Carlin)** .
- **Pulsars:** Spin wandering and measurements **(A. F. Vargas, J. O'Leary, L. Dunn, N. O'neill, T. Kimpson)** .

Data analysis:

- **GW search pipelines** **(S. Suvorova, B. Moran, R. evans, and L. Dunn. Former: P. Clearwater, and L. Sun)** .
- **GW searches** **(A. F. Vargas, C. Lee, J. Thong, L.Dunn, N. Low, T. Bu, and T. Cheuchitra)**
- **A Pulsar Timing Array pipeline** **(Lead: T. Kimpson, contributions from the rest of the group)** .
- **An HMM-based glitch and pulsar finder** **(J. O'leary, and L.Dunn)** .
- **Noise characterization** **(J. O'leary, and T. Kimpson)** .

A Bayesian scheme to infer braking indices for pulsar populations

- In order to estimate the population-level distribution of $n_{\rm pl}$, we combined the equation for $\langle n^2 \rangle$ with a hierarchical Bayesian scheme.
- For a test with 100 synthetic pulsars, 87% of the per-pulsar posteriors include $n_{\rm pl}$! — Similar accuracy is obtained for different population sizes.
- The idea is to apply the Bayesian scheme to real astronomical data (coming soon).



Validation test for a population of 100 synthetic pulsars with $n_{\rm pl}$ drawn from a Gaussian with mean $\mu_{\rm pl} = 4$ and standard deviation $\sigma_{\rm pl} = 4$. From: Vargas. A. F. and Melatos A. (submitted)