Core and crust contributions in overshooting glitches: the Vela pulsar 2016 glitch

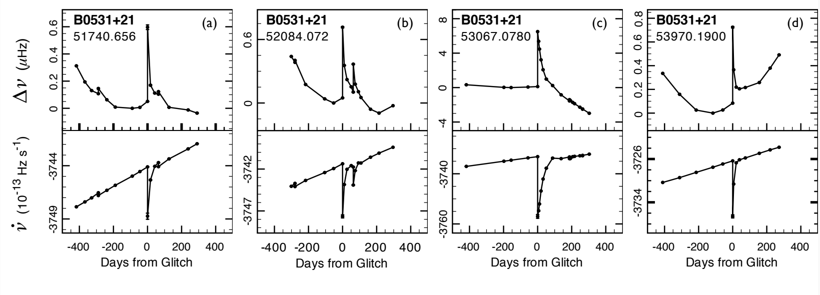
Alessandro Montoli

Università degli Studi di Milano &
Istituto Nazionale Fisica Nucleare

56th Karpacz Winter School in Theoretical Physics

Karpacz, 24th February 2020

Pulsar glitches



Four glitches of the Crab pulsar, Espinoza et al. (2011)

- Sudden acceleration in the rotation of a pulsar
- Two components, one spins down (normal), and one does not (superfluid)
- For some reason, the superfluid component occasionally releases angular momentum to the normal component
- The glitch trigger is still unknown

How does angular velocity evolves on short timescales?

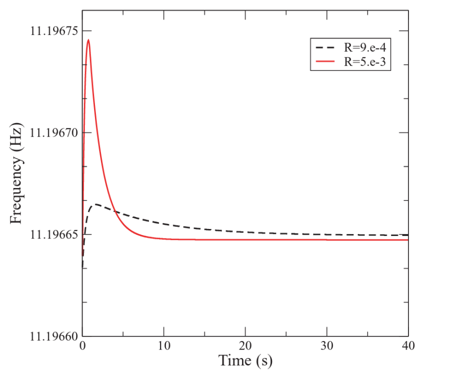


Figure taken from:

- Haskell et al. (2012)

See also:

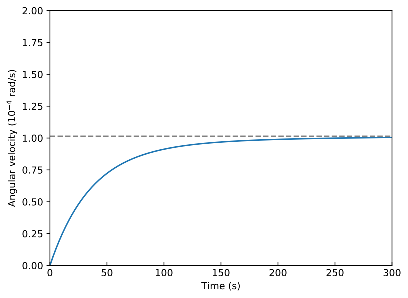
- Antonelli & Pizzochero (2017)
- Graber et al. (2018)
- Ashton et al. (2019)

This talk is based on:

Pizzochero, Montoli, Antonelli (2019) `arXiv:1910.00066` +

Montoli, Magistrelli, Antonelli, Pizzochero (2020), in preparation

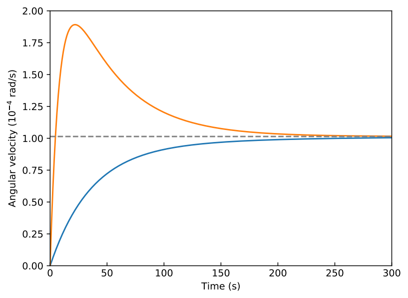
Rigidly-rotating components



$$\dot{\Omega}_p = -\frac{1}{x_p}\left(x_1\dot{\Omega}_1 + |\dot{\Omega}_\infty|\right)$$

$$\dot{\Omega}_1 = -b_1\left(\Omega_1 - \Omega_p\right)$$

Rigidly-rotating components

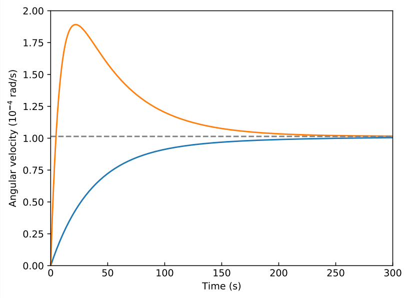


$$\dot{\Omega}_p = -\frac{1}{x_p}\left(x_1\dot{\Omega}_1 + x_2\dot{\Omega}_2 + |\dot{\Omega}_\infty|\right)$$

$$\dot{\Omega}_1 = -b_1\left(\Omega_1 - \Omega_p\right)$$

$$\dot{\Omega}_2 = -b_2\left(\Omega_2 - \Omega_p\right)$$

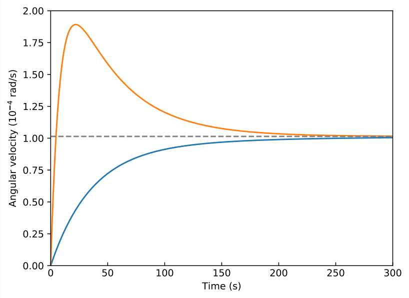
Working assumptions and some considerations



$$\dot{\Omega}_p = -\frac{1}{x_p}\left(x_1\dot{\Omega}_1 + x_2\dot{\Omega}_2 + |\dot{\Omega}_\infty|\right)$$
$$\dot{\Omega}_1 = -b_1\left(\Omega_1 - \Omega_p\right)$$
$$\dot{\Omega}_2 = -b_2\left(\Omega_2 - \Omega_p\right)$$

- The components are rigidly rotating
- We assume that $x_1 + x_2 + x_p = 1$
- We are using a Newtonian model (the rise time should be corrected by a factor of $\lesssim 2$, see Sourie et al. 2017 and Gavassino et al. 2020)
- There are two different initial lags Ω^0_{1p}, Ω^0_{2p} between the two superfluid components the normal component

Solution to the system



$$\dot{\Omega}_p = -\frac{1}{x_p}\left(x_1\dot{\Omega}_1 + x_2\dot{\Omega}_2 + |\dot{\Omega}_\infty|\right)$$

$$\dot{\Omega}_1 = -b_1\left(\Omega_1 - \Omega_p\right)$$

$$\dot{\Omega}_2 = -b_2\left(\Omega_2 - \Omega_p\right)$$

It is possible to solve analytically the system, in order to obtain the angular velocity of the normal component with respect to the spin down of the star.

$$\Delta\Omega_p(t) = \Delta\Omega_p^\infty\left[1 - \omega\, e^{-t\lambda_+} - (1-\omega)\, e^{-t\lambda_-}\right]$$

where $\lambda_\pm$, $\Delta\Omega_p^\infty$, ω are analytical functions of $x_{1,2}$, $\tau_{1,2}$, $\Omega^0_{1,2p}$.

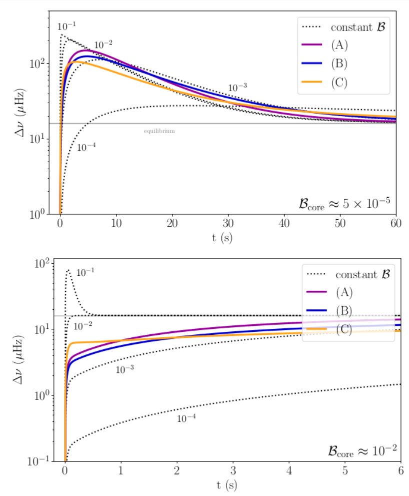
Overshoots!

An overshoot can occur when there is a maximum in $\Delta\Omega_p(t)$.

$$\Rightarrow \omega > 1$$

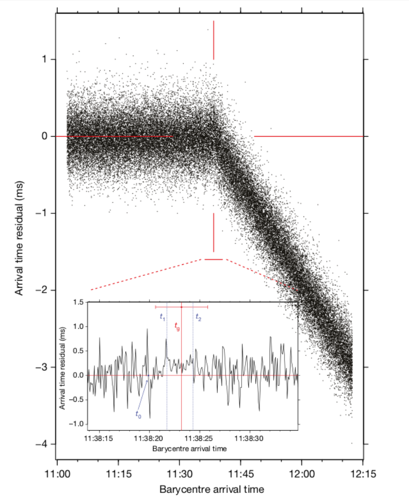
It can be shown that, with some simplifying assumptions, the overshoot condition corresponds to:

$$b_1/b_2 < 1$$



Graber et al. 2018

Application to the 2016 Vela glitch



Palfreyman et al. 2018

Palfreyman et al. (2018) measured a glitch on the Vela pulsar with the best precision ever achieved.
Our aim is that of fitting the data with the three-component model in order to obtain the value of the parameters $x_{1,2}$, $b_{1,2}$, $\Omega^0_{1,2p}$.

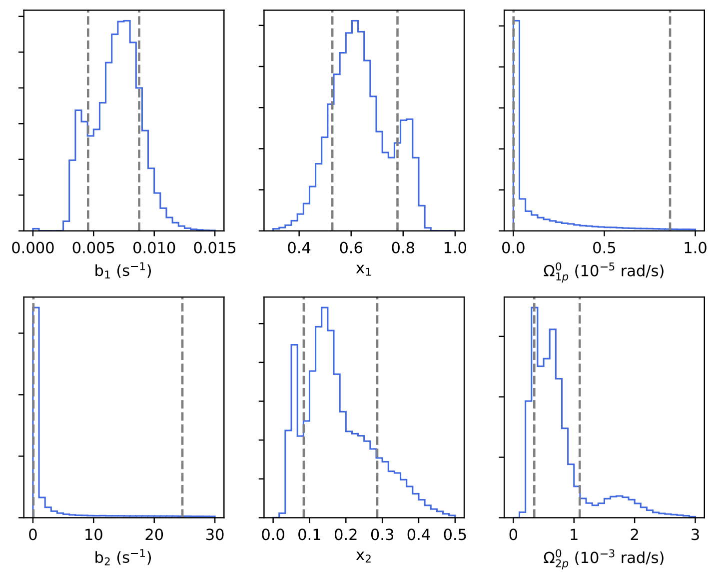
Bayesian analysis

$$P(\mathcal{P}\,|\,\mathcal{D}) = \frac{P(\mathcal{D}\,|\,\mathcal{P})\,P(\mathcal{P})}{P(\mathcal{D})}$$

- $\mathcal{P}$: parameters of the model ($x_{1,2}$, $b_{1,2}$, $\Omega_{1,2p}$, t_g, t_M, Δr_0).
- $\mathcal{D}$: the data in Palfreyman et al. (2018)
- $P(\mathcal{D}\,|\,\mathcal{P})$: likelihood
- $P(\mathcal{P})$: prior
- $P(\mathcal{D})$: marginalised likelihood, a.k.a. evidence
- $P(\mathcal{P}\,|\,\mathcal{D})$: posterior

We keep the prior as uninformative as possible.

Marginalised posterior distribution (for some of the variables)



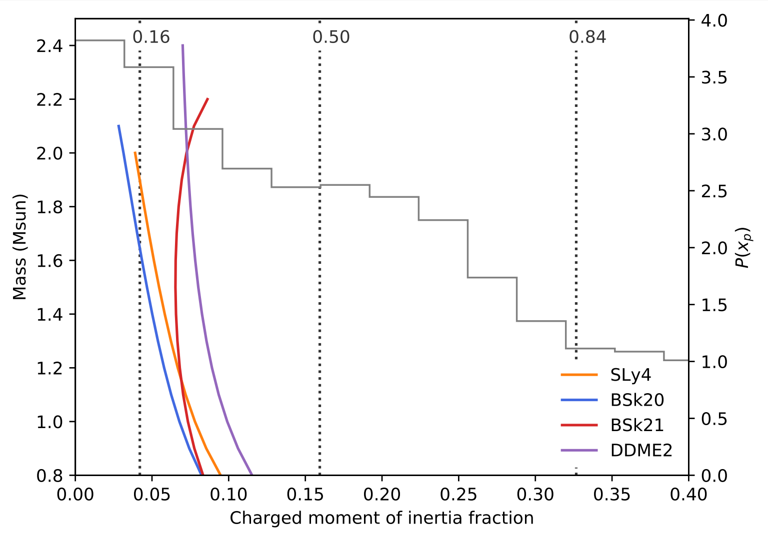
Are we completely sure about it?

The fit has been performed with a prior on the moments of inertia fraction given by:

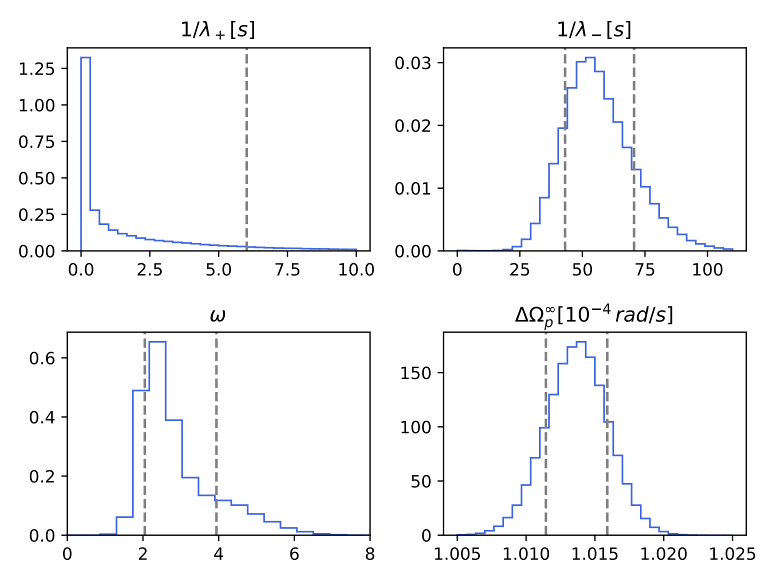
$$x_1, x_2 \sim \begin{cases} \text{Unif}(0,1)\text{Unif}(0,1) & \text{if } x_1 + x_2 < 1 \\ 0 & \text{elsewhere} \end{cases}$$

Tightening the prior to 0.05 would yield a much lower evidence for this model, and a natural logarithm of the Bayes factor of 5.6 proves it to be very unlikely.

Normal component



Other variables

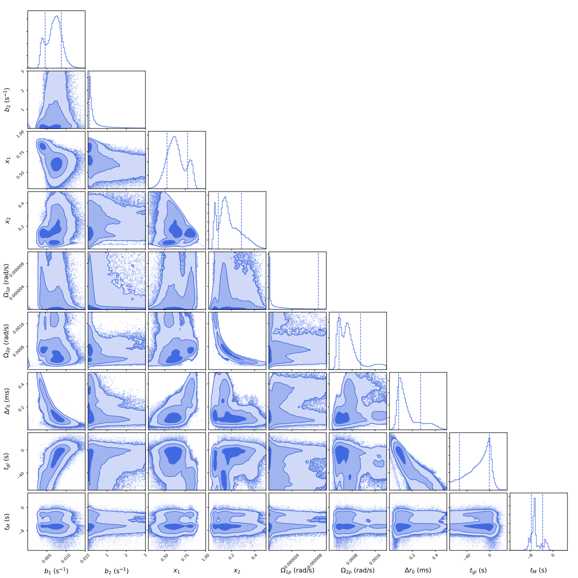


Conclusions

- The results obtained in this work, although with a simple toy model, is compatible with much of the literature.
- The pinned superfluid cannot be contained just in the crust of the star (see also works on the activity parameter).
- It is also possible to obtain an estimate of the coupling parameters between the superfluid components and the normal component.
- Importance of a Bayesian approach: the output of this inference can be reused for another Vela glitch.

Thank you for your attention!

Cornerplot

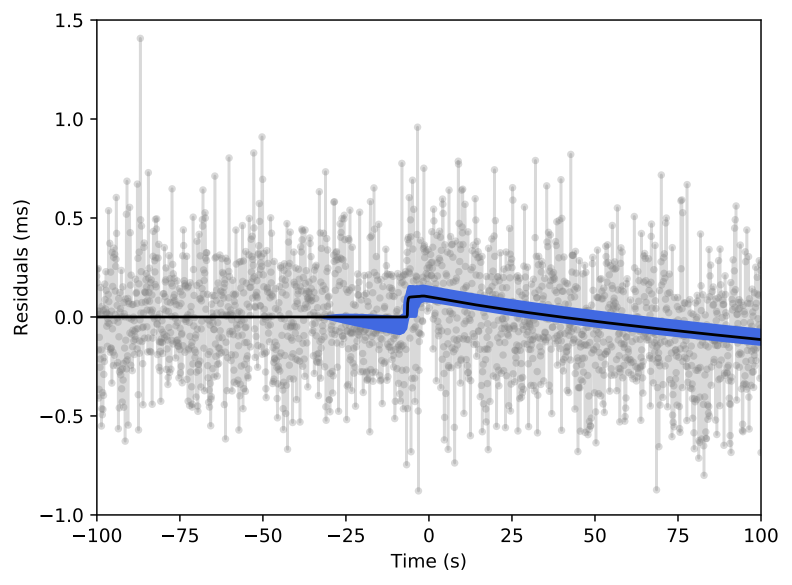


b_1 (s^{-1})
b_2 (s^{-1})
x_1
x_2
Ω_{1p} (rad/s)
Ω_{2p} (rad/s)
Δr_0 (ms)
t_{gl} (s)
t_M (s)

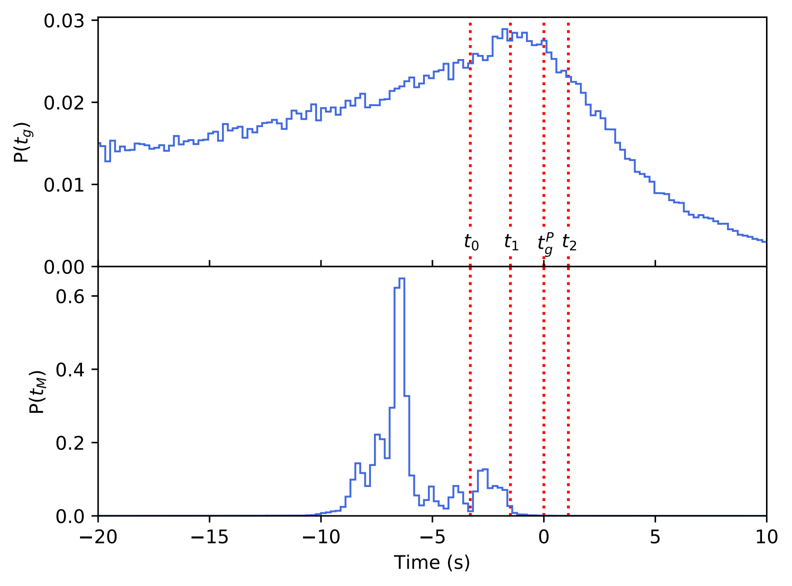
Posterior

Variable	16th percentile	Median	84th percentile
b_1	0.004	0.007	0.009
b_2	0.08	0.37	24.64
x_1	0.53	0.63	0.78
x_2	0.08	0.16	0.29
Ω^0_{1p}	1.06e-08	5.18e-07	8.61e-06
Ω^0_{2p}	0.0003	0.0006	0.0011
Δr_0	0.08	0.12	0.27
t_g	-53.1	-18.2	-1.1
t_M	-7.59	-6.46	-3.61

Fit of the residuals



Times


0.03
0.02
0.01
0.00
P(t_g)
t_0
t_1
t_g^P
t_2
0.6
0.4
0.2
0.0
P(t_M)
−20
−15
−10
−5
0
5
10
Time (s)