New measurements of pulsar braking indices
(obtained via phase-coherent timing)

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Outline

- Pulsar spin-down and the braking index
- How to measure a braking index
- PSR J1846-0258
- PSR B1509-58
- PSR B0540-69
- Other measurements of n
- Possible physical explanations of $n<3$

Pulsar Spin-down

- In general, pulsar spin-down is assumed to be of the form:

$$\dot{\nu} = -K\nu^n$$

- Then the braking index, *n*, is given by:

$$n = \nu\ddot{\nu}/\dot{\nu}^2$$

The braking index:
Some simple physical expectations

- The braking index tells us something about the physics causing the spin down of the pulsar
- n=3: Only magnetic dipole radiation
- n=1: Only pulsar wind
- n=5: Magnetic or gravitational quadrupole radiation

$$\dot{\nu} = -K\nu^n$$

How to measure *n*? A recipe

1. Find a pulsar that:
    1. Spins down quickly
    2. Experiences few, small, infrequent glitches
    3. Has low-level timing noise

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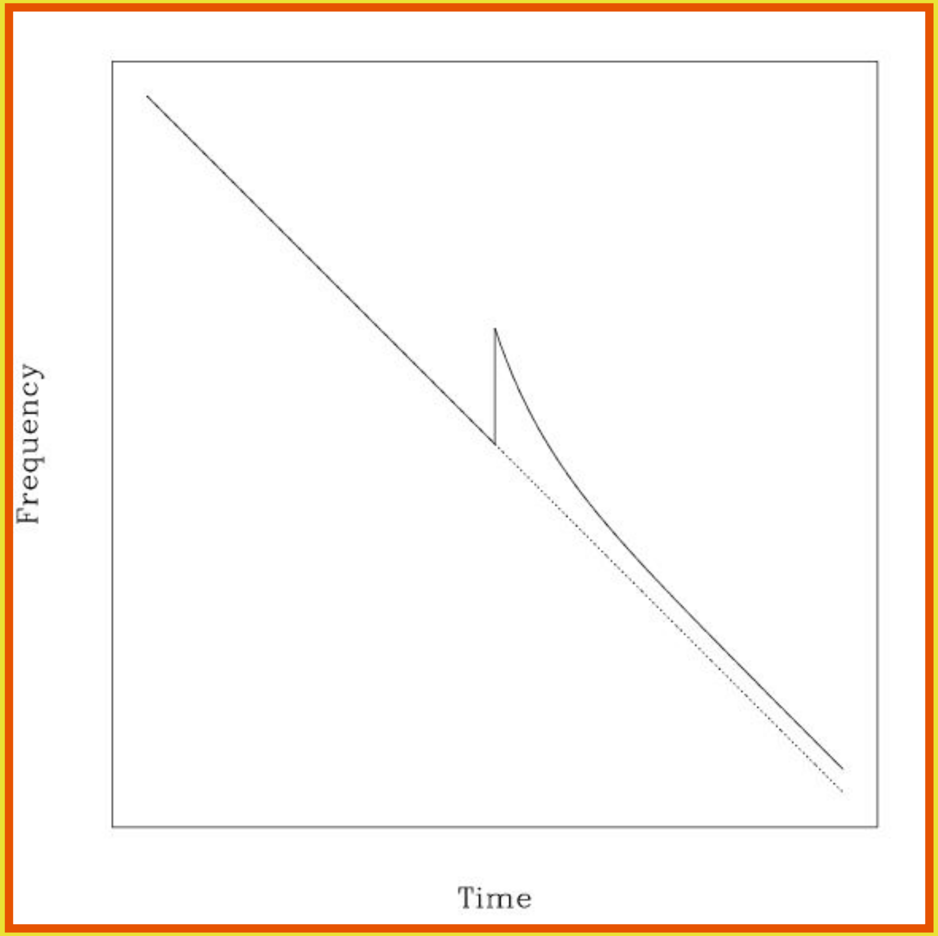
--> **Very young pulsar!**

Young Pulsars

	Pulsar	P (ms)	$\dot{P}$ (10^{-12} s/s)	τ_c
*	J1846-0258	324	7.1	723
*	Crab	33	0.42	1240
*	B1509-58	150	1.5	1550
*	J1119-6127	408	4.0	1610
*	B0540-69	50	0.48	1670
	J1124-5916	135	0.75	2870
	J1930+1852	137	0.75	2890
	J0537-6910	16	0.05	4900
	J0205+6449	66	0.19	5370
*	Vela	89	0.13	11000

Glitches

- Sudden spin-up of the pulsar
- Often a change in $\dot{\nu}$
- $\Delta\nu / \nu \sim 10^{-9} - 10^{-6}$
- $\tau_c \geq 5$ kyr: glitches typically larger
- The fewer (and smaller) the better for measuring *n*



Timing Noise

- Low-frequency stochastic process superimposed on deterministic spin-down
- Correlated with frequency derivative
- Of unknown origin:
  - Magnetospheric current fluctuations
  - Free precession
  - Gravitational torques
  - Random pinning & unpinning of superfluid vortices

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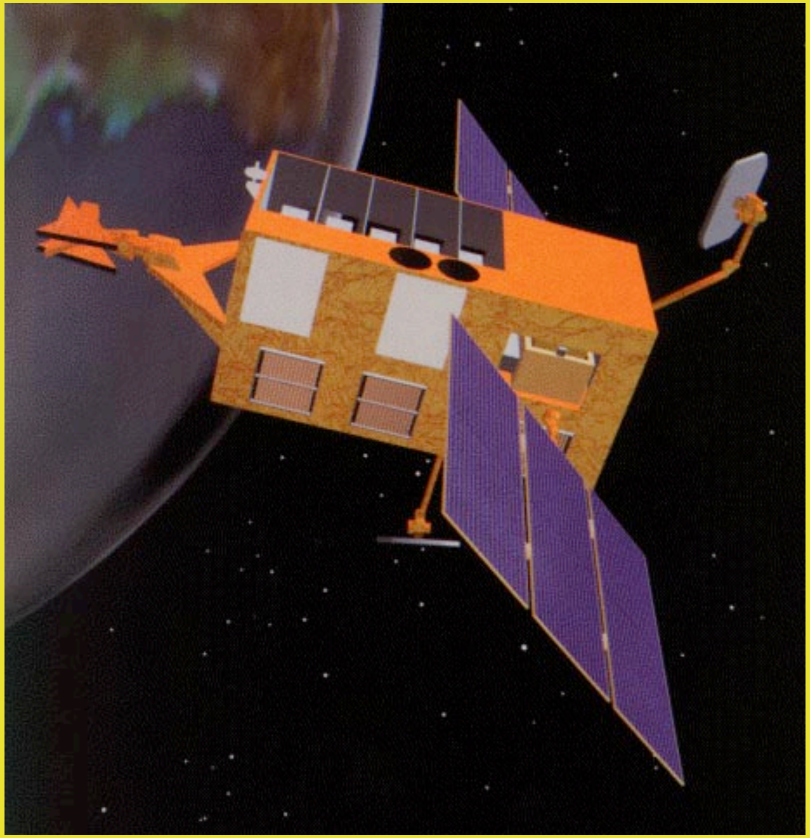
4. Rossi X-ray Timing Explorer

- Indispensable for timing young pulsars
- Many young pulsars best (or only) viewed in X-rays: e.g. PSR B0540-69, PSR J1846-0258, 3C 58, G11
- Proportional Counter Array
- 1 degree field of view
- 2-60 keV energy range
- ~100us absolute time resolution



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3. Phase-coherent timing

Phase-coherent Timing

- Measure pulse Times Of Arrival (TOAs)
- Taylor expansion of pulse phase
- Account for each turn of pulsar

$$\phi(t) = \phi(t_0) + \nu_0(t - t_0) + \frac{1}{2}\dot{\nu}_0(t - t_0)^2 + \frac{1}{6}\ddot{\nu}_0(t - t_0)^3 + \ldots$$

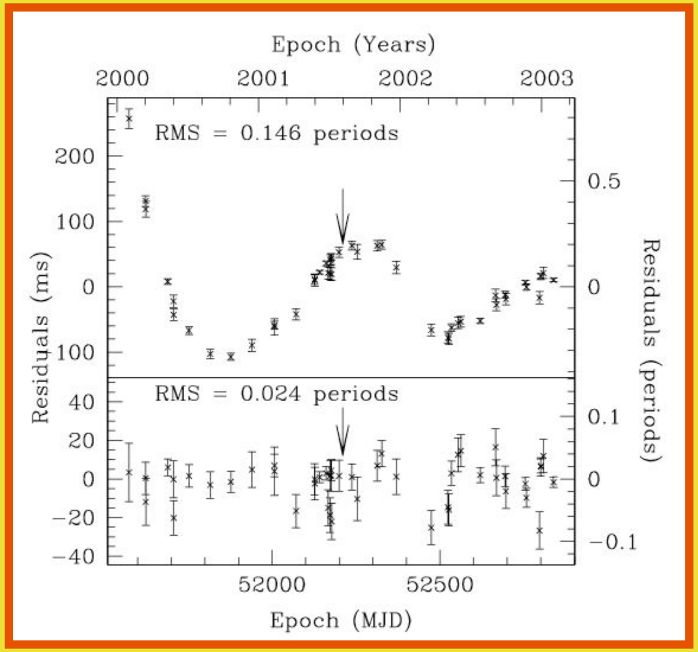
- Input: TOAs + initial spin parameters
- Output: Refined parameters +timing residuals
- Glitches can also be modelled

PSR J1846-0258

- Discovered in 1999 with *RXTE* (Gotthelf et al 2000)
- Located at the center of SNR Kes 75
- P=324 ms
- $\tau_c = P/2\dot{P} = 723 yr$
- $B \sim 5 \times 10^{13}$ G
- Very similar to PSR J1119-6127: will *n* be similar as well?

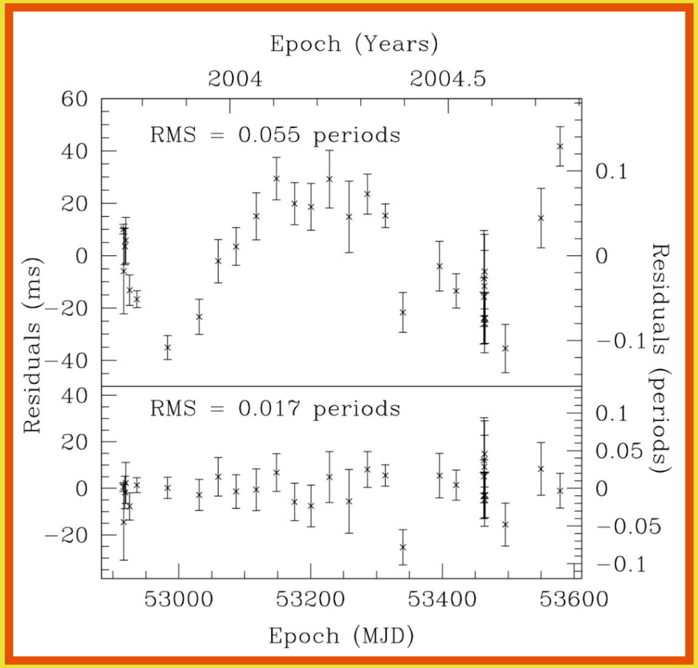
Phase-coherent timing solutions

- Two timing solutions span 5.5 yr
- Phase lost over an 80 day gap:



Glitch?

Timing noise?



Reason for phase loss ambiguous!

First timing solution

- Glitch near MJD 52210
- Glitch parameters:
  - $\Delta\nu/\nu = 2.5(2) \times 10^{-9}$
  - $\Delta\dot{\nu}/\dot{\nu} \sim 9.3(1) \times 10^{-4}$
- Spin Parameters:

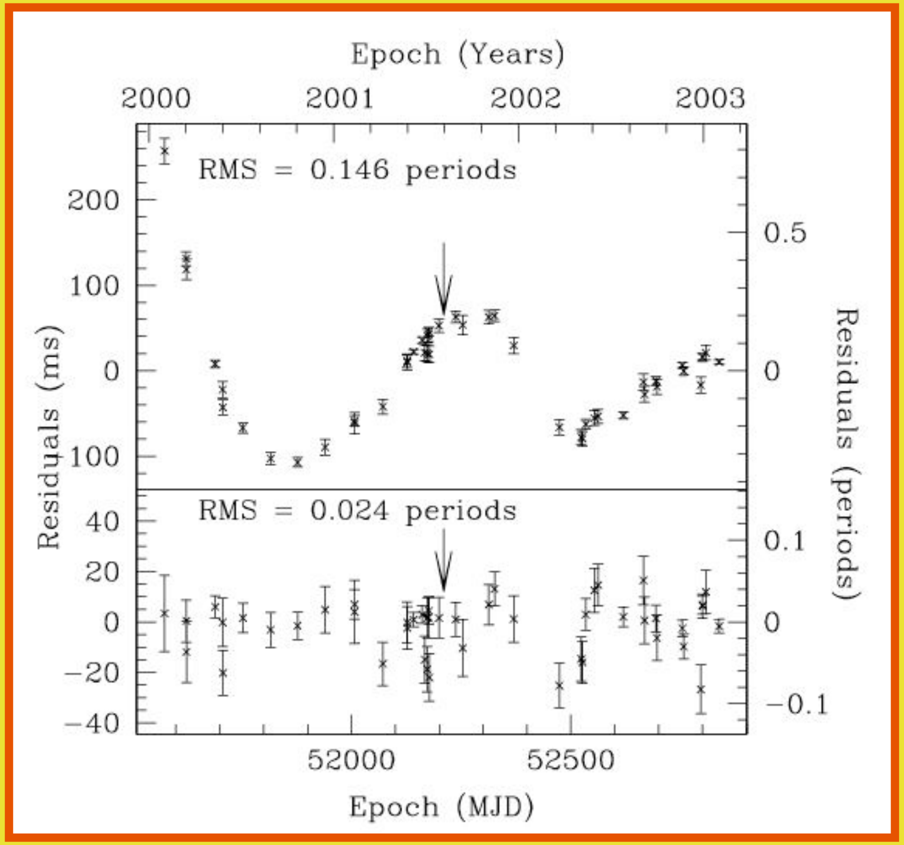
$$\nu = 3.0782148166(9)s^{-1}$$

$$\dot{\nu} = -6.71563(1)\times 10^{-11} s^{-2}$$

$$\ddot{\nu} = 3.87(2)\times 10^{-21} s^{-3}$$

- $n = 2.64$ +/-0.01
- 8 frequency derivatives needed to 'whiten' residuals: timing noise, possibly unmodelled glitch recovery

Timing residuals for 3.5 yr



Second timing solution

- No glitches detected
- Spin parameters:

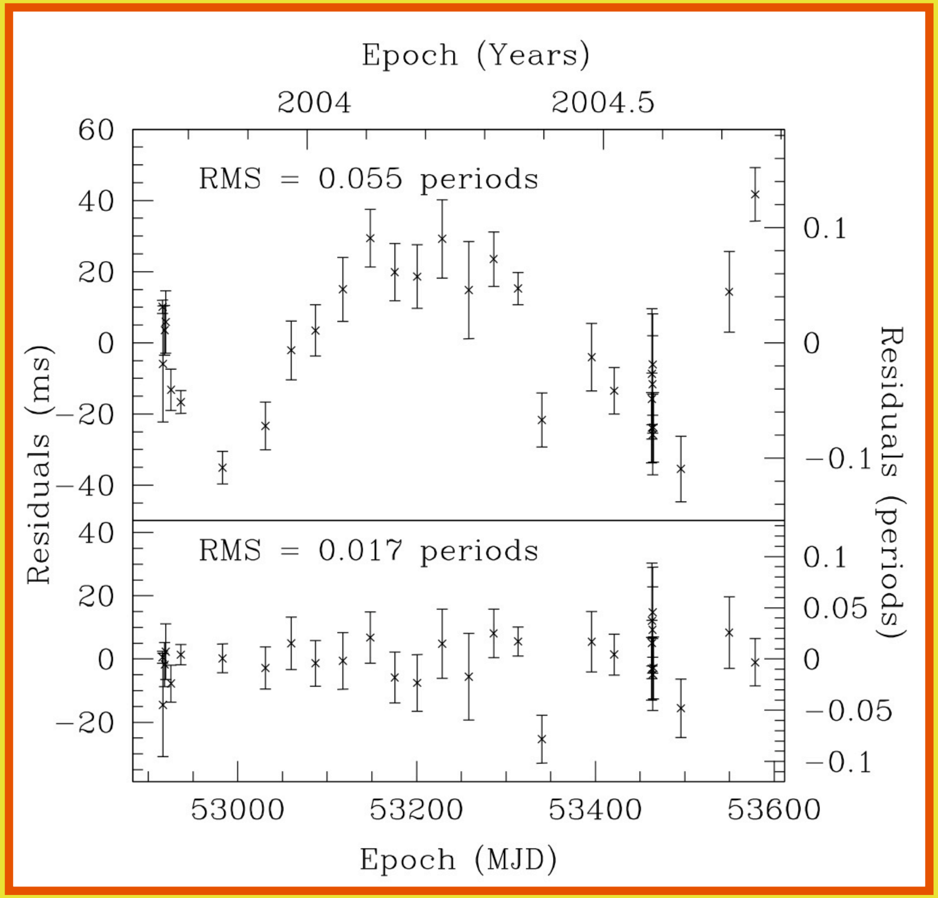
$$\nu = 3.070458592(1) s^{-1}$$

$$\dot{\nu} = -6.67793(5) \times 10^{-11} s^{-2}$$

$$\ddot{\nu} = 3.89(4) \times 10^{-21} s^{-3}$$

- n=2.68+/-0.03
- 5 frequency derivatives fitted to remove timing noise, possibly glitch recovery

Timing residuals for 1.8 years



The braking index of PSR J1846-0258

- Two independent, phase-coherent timing solutions in agreement
- Average braking index from both phase-coherent timing solutions:

$$n = 2.65 \text{ +/- } 0.01$$

Implications of *n* measurement

- For *n*=2.65, age estimate is larger:

$$\tau \leq -\frac{1}{n-1}\frac{\nu}{\dot{\nu}} \lesssim 884\,\mathrm{yr}$$

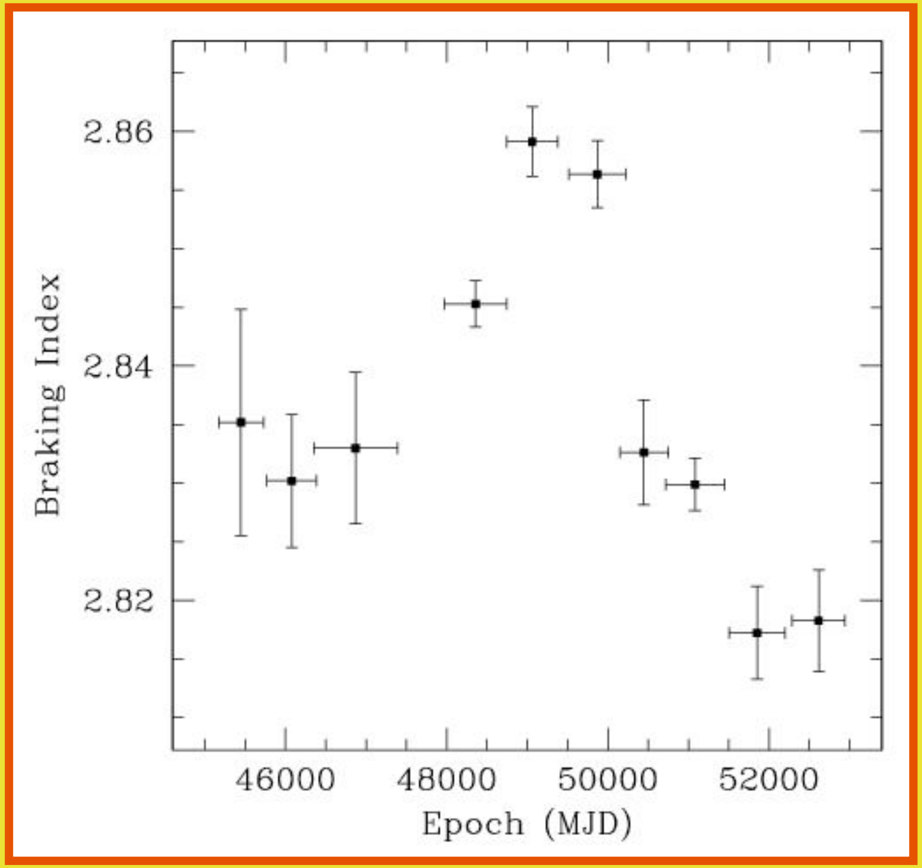
- Estimate still smaller than the Crab pulsar
- Dipole magnetic field overestimated - perhaps *not* magnetar strength?
- PSR J1119-6127 --> *n*=2.91+/-0.05

PSR B1509-58

- Estimated age ~1700 yr
- P=150ms, B=1.5x10^{13}G
- 21.3 yr radio timing data (Molonglo, Parkes), 7.5 yr *RXTE* data
- **No glitches!**
- n=2.839+/-0.003

Braking Index Variations

- Variations in *n*:
  - PSR B1509-58 ~1.5%
  - Kes 75 ~5%
  - Crab pulsar ~5%
- Likely due to timing noise, glitch recovery



Measurements of *n* for PSR B1509-58 over 21 years

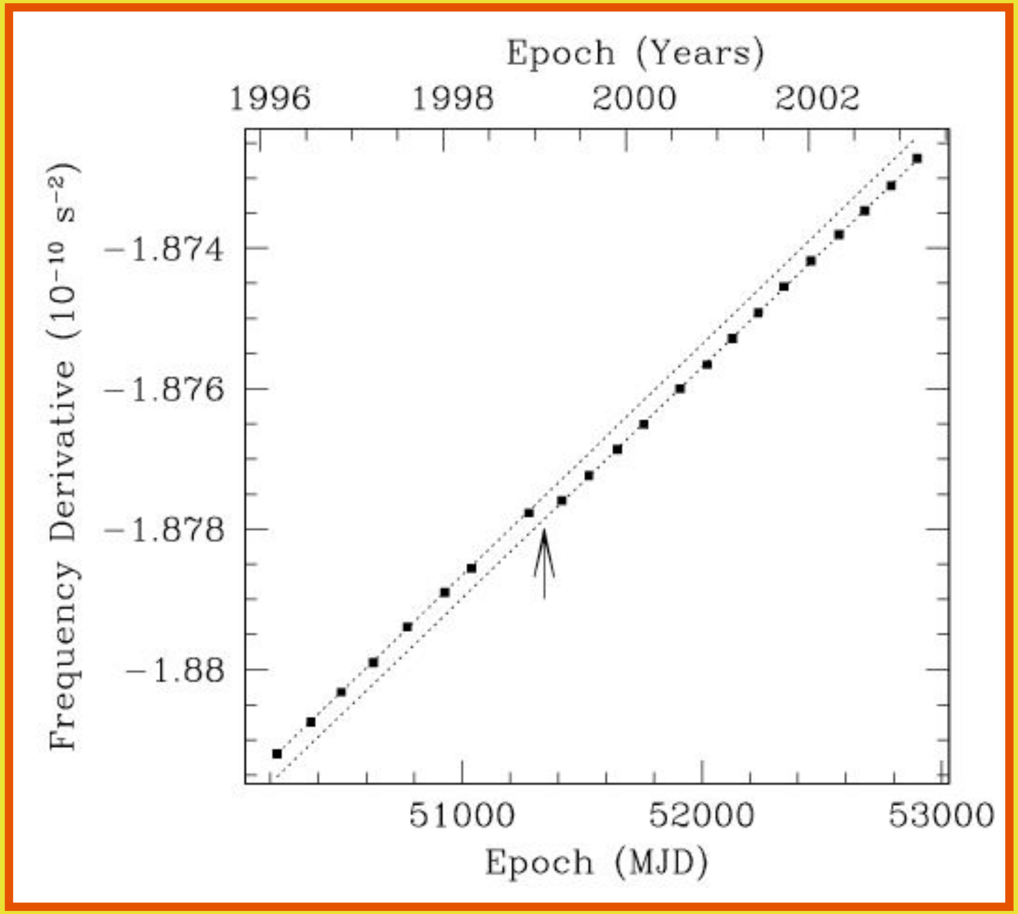
PSR B0540-69

- 'Crab Twin' pulsar
- P=50ms, B~5x10^{12}G
- Many conflicting values of *n* in literature
- 7.6 yr RXTE data
- Small glitch:

$$\Delta\nu/\nu \sim 1.4\times10^{-9}$$

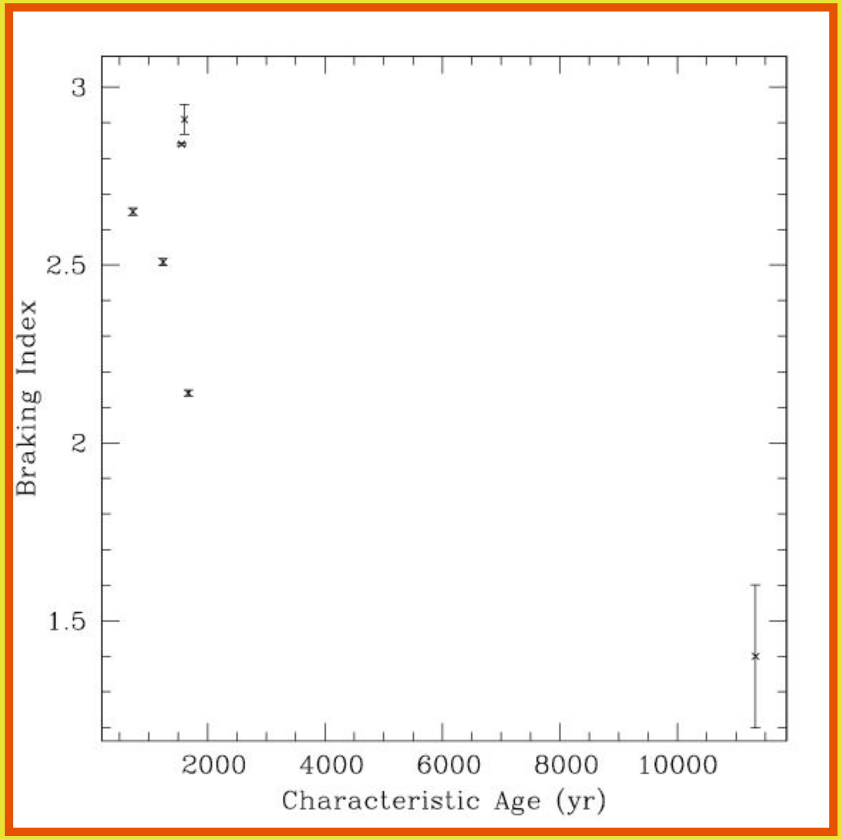
$$\Delta\dot{\nu}/\dot{\nu} \sim 1.33\times10^{-4}$$

- *n*=2.140+/-0.009



All *n* less than 3

- All 6 pulsars with measured braking indices have significant measurements of $n<3$
- Large scatter in observed values of n
- Assumption of $n=3$ used in estimation of B and τ



In addition to magnetic dipole radiation, another physical process must contribute to the torque acting on (young) pulsars!

Possible Physical Explanations for *n*<3

- Growth or counter-alignment of *B* (e.g. Blandford & Romani 1988)
- Propeller effect due to a fallback disk (e.g. Alpar 2001)
- Particle outflow: Kinetic energy flow dominates over Poynting flux
- Misaligned dipole + plasma (e.g. Contopoulos & Spitkovsky 2005)
- ***Unfortunately, none of these provide predictions for n***

Rotating magnet of variable size
(Melatos 1997)

- Postulate: inner magnetosphere of $R_{NS} << R_v \sim< R_{LC}$
- Inner magnetosphere corotates rigidly with NS
- Model predicts: $2<n<3$ and n-->3 as the pulsar ages.
- Predicts n given ν, $\dot{\nu}$, α
- Roughly agrees with n for PSR B1509-58, PSR B0540-69, Crab
- PSR J1119-6127: α not well determined (Crawford 2001)
- Does not agree with n for Vela
- **For PSR J1846-0258, n=2.65+/-0.01, predict α=8.1-9.6°**

Summary

- PSR J1846-0258: n=2.65+/-0.01, at least one glitch
- PSR B1509-58: n=2.839+/-0.003, no glitches
- PSR B0540-69: n=2.140+/-0.009, one small glitch detected
- All measured values are $n<3$
- Large scatter exists among n
- Various explanations of why $n<3$ exist, though none can explain all measurements AND provide predictions.