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Could low braking-index pulsar J1734-3333 evolve into a magnetar?

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Contents

Introduction

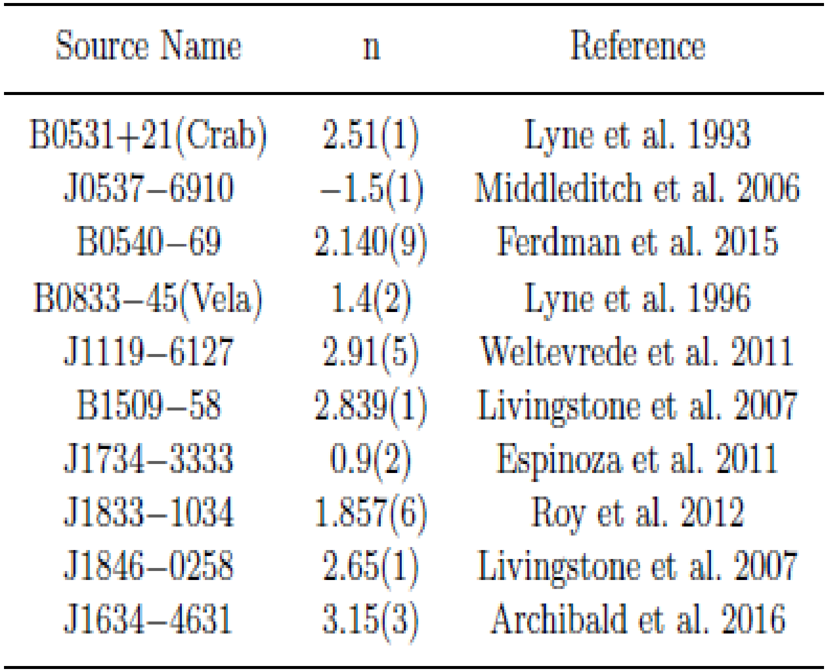
- The secular decrease in the angular velocity of a pulsar is described by

$$\dot{\Omega} \propto \Omega^{n}$$

- Baking index n is defined by

$$n = \frac{\Omega\ddot{\Omega}}{\dot{\Omega}^{2}} = \frac{\nu\ddot{\nu}}{\dot{\nu}^{2}} = 2 - \frac{P^{2}\ddot{P}}{\dot{P}^{2}}$$

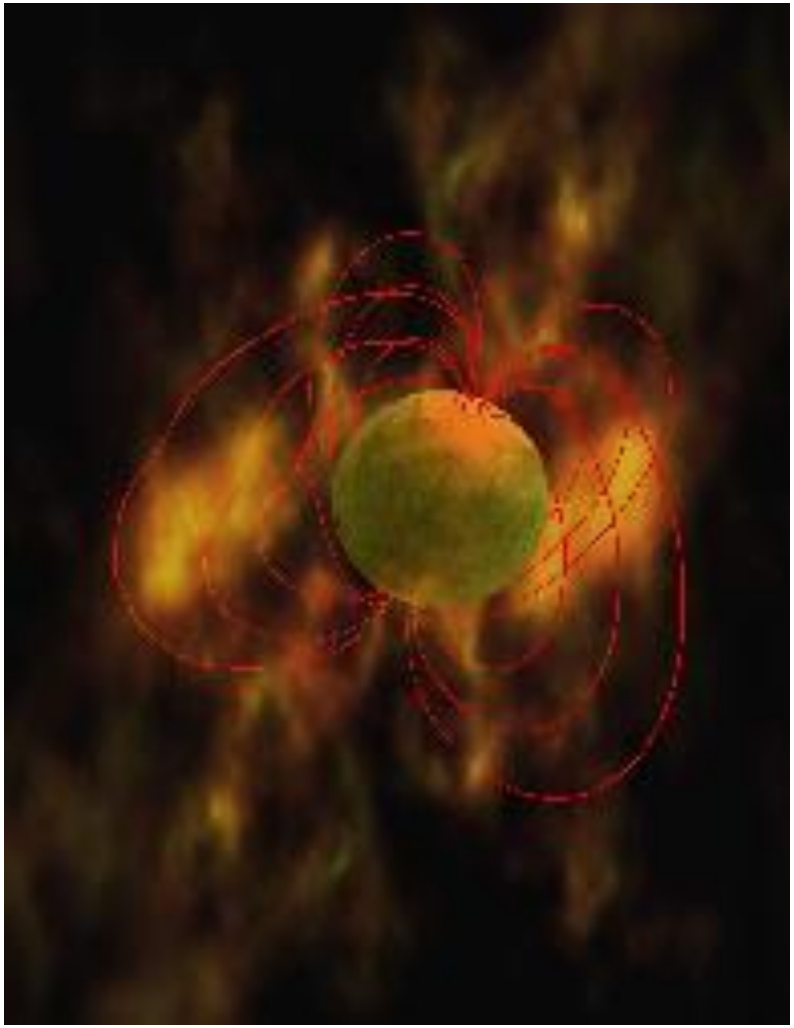
Published braking indices of pulsars



Source Name	n	Reference
B0531+21(Crab)	2.51(1)	Lyne et al. 1993
J0537−6910	−1.5(1)	Middleditch et al. 2006
B0540−69	2.140(9)	Ferdman et al. 2015
B0833−45(Vela)	1.4(2)	Lyne et al. 1996
J1119−6127	2.91(5)	Weltevrede et al. 2011
B1509−58	2.839(1)	Livingstone et al. 2007
J1734−3333	0.9(2)	Espinoza et al. 2011
J1833−1034	1.857(6)	Roy et al. 2012
J1846−0258	2.65(1)	Livingstone et al. 2007
J1634−4631	3.15(3)	Archibald et al. 2016

Introduction

- Magnetars are neutron stars powered by magnetic field energy.
- 28 magnetar candidates.
- Classed as Anormous X-ray pulsars (AXPs) & Soft Gamma-ray repeaters (SGRs)
- Due to strong timing noise and lake of persistent emission, it is hard to measure their braking indices observationally.



Observational characteristics of magnetars

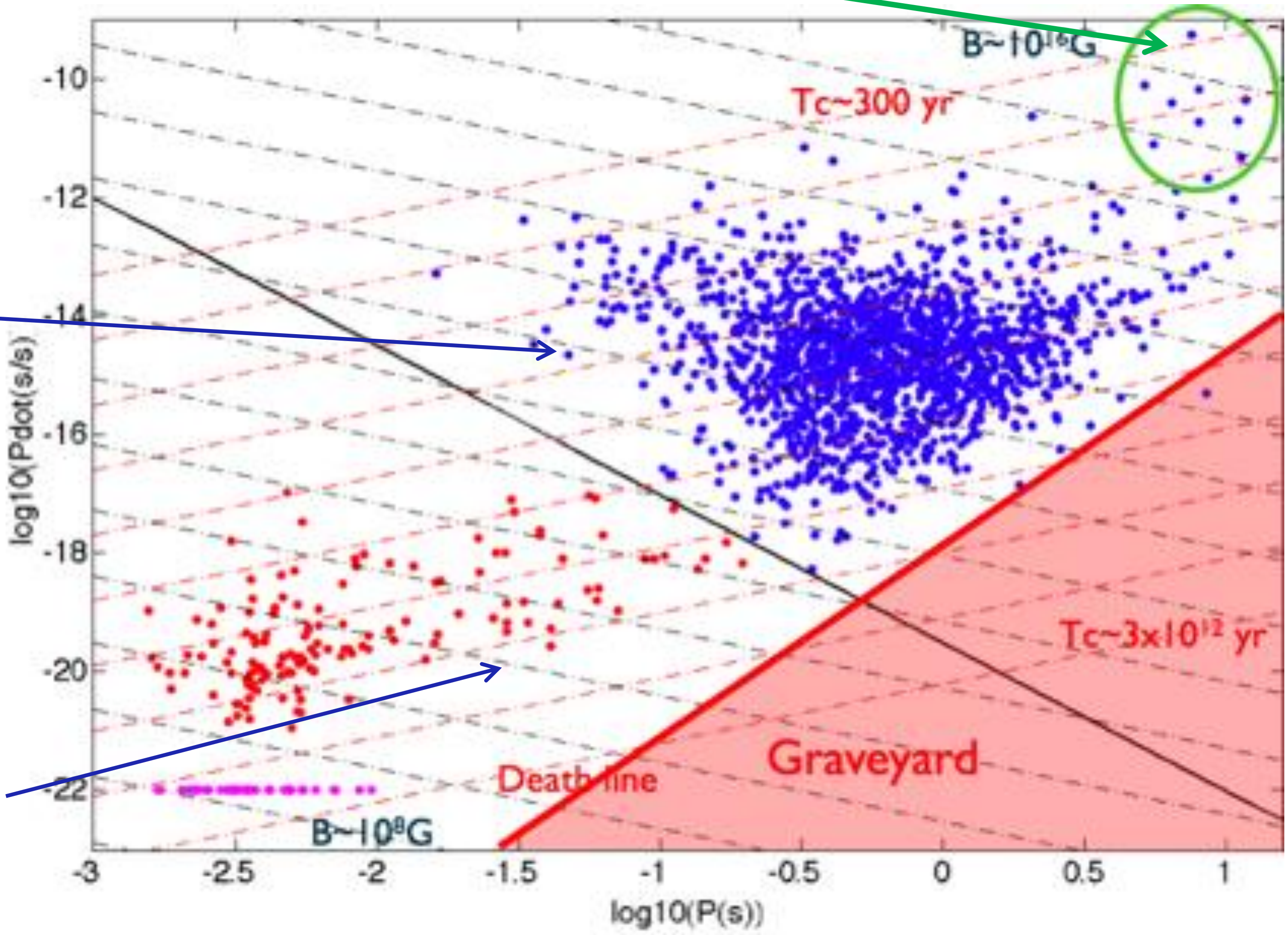
- **Spin period： 2 – 12 sec**
- **Period derivative: 10^{-14} – 10^{-10} s/s**
- **Dipolar magnetic field: 10^{13} – 10^{15} G**
- **Persistent soft X-ray luminosity (10^{33}-10^{35} erg/s) higher than their rotational energy loss**
- **X-ray burst /flare**

  luminosity > 10^{37} erg/s

  giant bursts Lx > 10^{42} erg/s

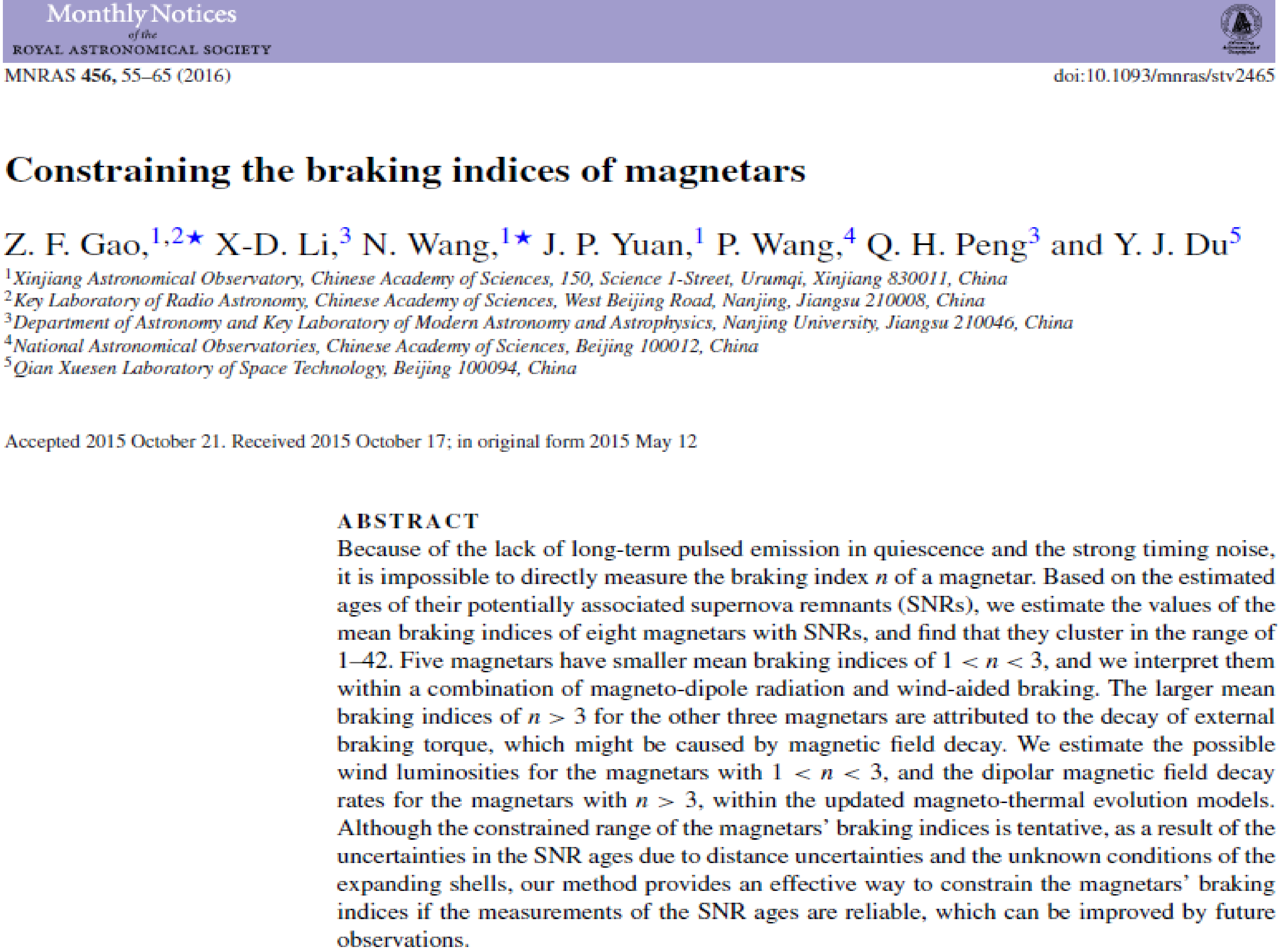
Distribution of pulsars

AXPs & SGRs



Radio pulsars

Millisecond pulsars



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Constraining the braking indices of magnetars

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ABSTRACT

Because of the lack of long-term pulsed emission in quiescence and the strong timing noise, it is impossible to directly measure the braking index n of a magnetar. Based on the estimated ages of their potentially associated supernova remnants (SNRs), we estimate the values of the mean braking indices of eight magnetars with SNRs, and find that they cluster in the range of 1–42. Five magnetars have smaller mean braking indices of $1 < n < 3$, and we interpret them within a combination of magneto-dipole radiation and wind-aided braking. The larger mean braking indices of $n > 3$ for the other three magnetars are attributed to the decay of external braking torque, which might be caused by magnetic field decay. We estimate the possible wind luminosities for the magnetars with $1 < n < 3$, and the dipolar magnetic field decay rates for the magnetars with $n > 3$, within the updated magneto-thermal evolution models. Although the constrained range of the magnetars' braking indices is tentative, as a result of the uncertainties in the SNR ages due to distance uncertainties and the unknown conditions of the expanding shells, our method provides an effective way to constrain the magnetars' braking indices if the measurements of the SNR ages are reliable, which can be improved by future observations.

Magnetar pindown evolution

Z. F. Gao, et al. MNRAS, 456, 55-65 (2016)

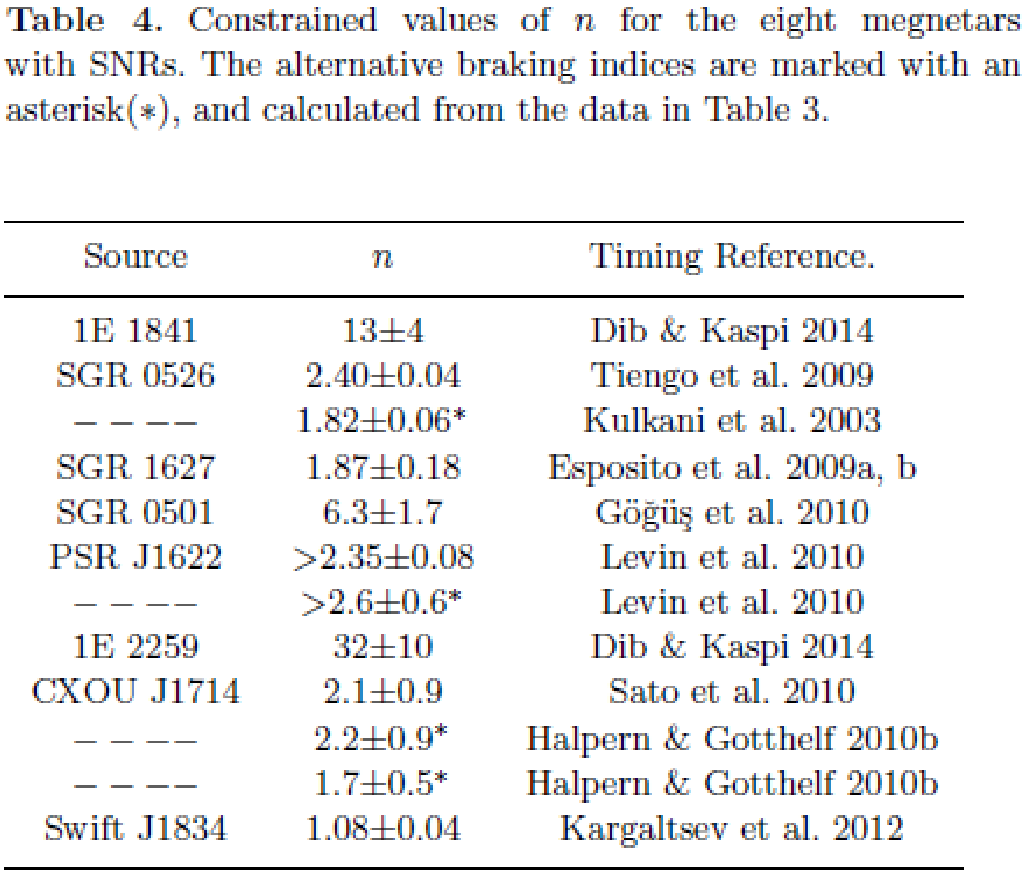
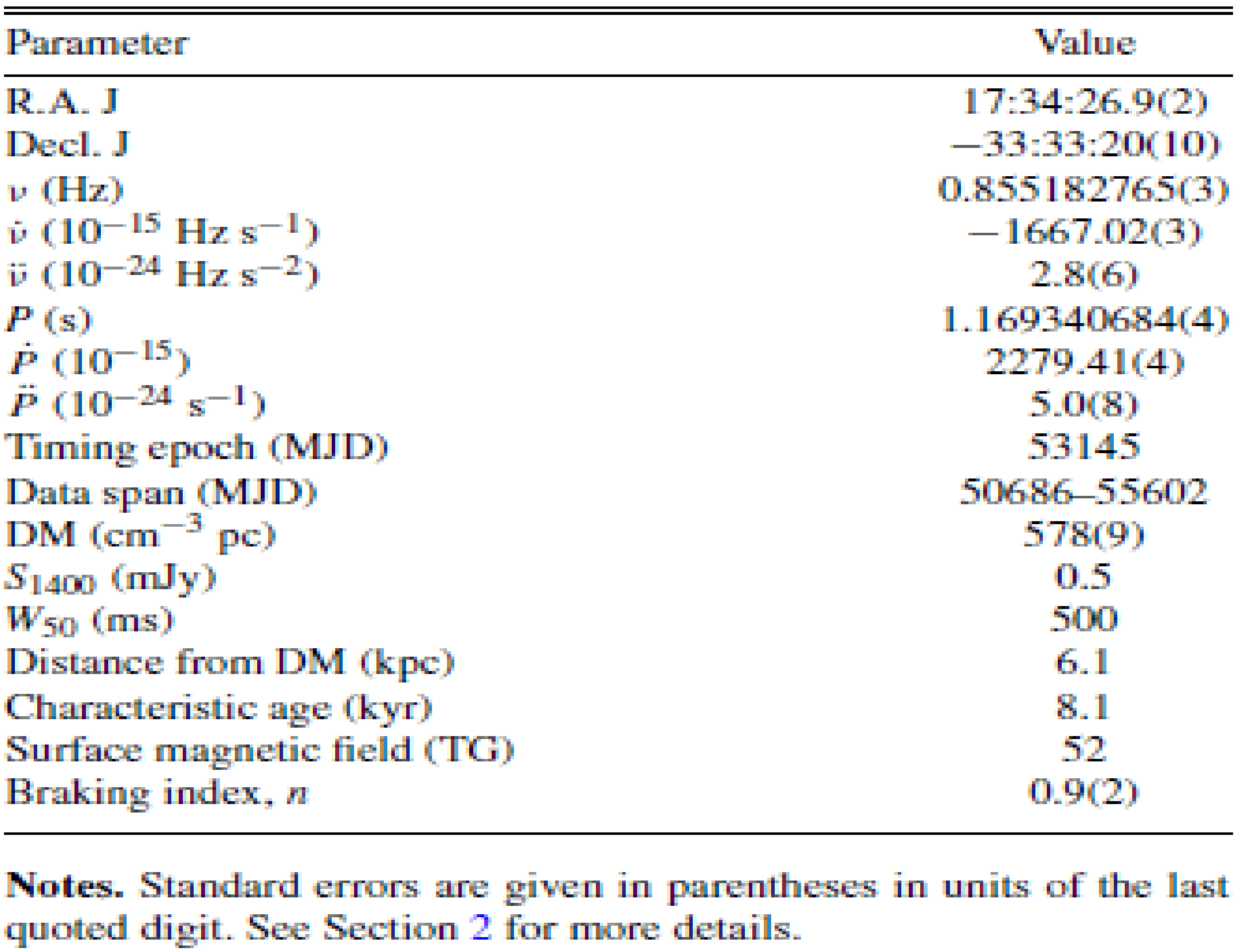


Table 4. Constrained values of n for the eight megnetars with SNRs. The alternative braking indices are marked with an asterisk($*$), and calculated from the data in Table 3.

Source	n	Timing Reference.
1E 1841	13±4	Dib & Kaspi 2014
SGR 0526	2.40±0.04	Tiengo et al. 2009
– – ––	1.82±0.06*	Kulkani et al. 2003
SGR 1627	1.87±0.18	Esposito et al. 2009a, b
SGR 0501	6.3±1.7	Göğüş et al. 2010
PSR J1622	>2.35±0.08	Levin et al. 2010
– – ––	>2.6±0.6*	Levin et al. 2010
1E 2259	32±10	Dib & Kaspi 2014
CXOU J1714	2.1±0.9	Sato et al. 2010
– – ––	2.2±0.9*	Halpern & Gotthelf 2010b
– – ––	1.7±0.5*	Halpern & Gotthelf 2010b
Swift J1834	1.08±0.04	Kargaltsev et al. 2012

Basic information for PSRJ1734-3333



Parameter	Value
R.A. J	17:34:26.9(2)
Decl. J	−33:33:20(10)
ν (Hz)	0.855182765(3)
$\dot{\nu}$ (10^{-15} Hz s^{-1})	−1667.02(3)
$\ddot{\nu}$ (10^{-24} Hz s^{-2})	2.8(6)
P (s)	1.169340684(4)
$\dot{P}$ (10^{-15})	2279.41(4)
$\ddot{P}$ (10^{-24} s^{-1})	5.0(8)
Timing epoch (MJD)	53145
Data span (MJD)	50686–55602
DM (cm^{-3} pc)	578(9)
S_{1400} (mJy)	0.5
W_{50} (ms)	500
Distance from DM (kpc)	6.1
Characteristic age (kyr)	8.1
Surface magnetic field (TG)	52
Braking index, n	0.9(2)

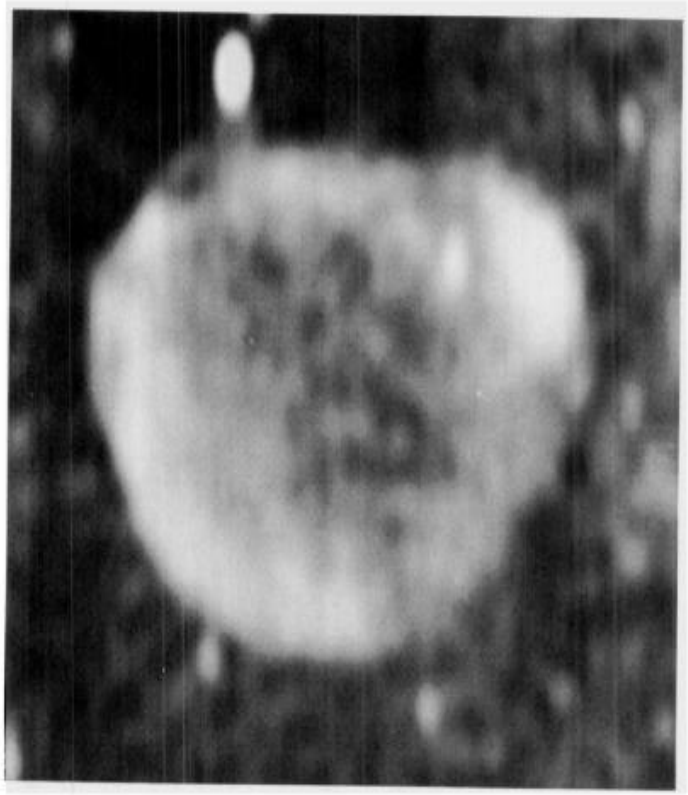
Notes. Standard errors are given in parentheses in units of the last quoted digit. See Section 2 for more details.

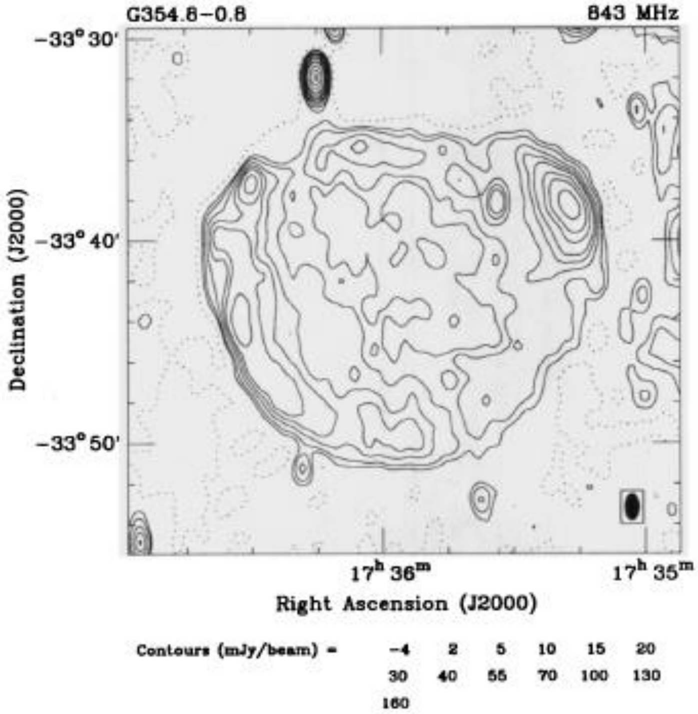
$$n = 0.9 \pm 0.2$$

Why n < 3 ?

- Neutrino and photon radiation (Peng et al. 1982);
- Combination of dipole radiation and the propeller torque applied by debris-disk (e.g., Alpar & Baykal 2006);
- Frequent glitches, as well as magnetosphere currents (e.g., Chen 2009).
- Wind braking (Tong et al. 2013)
- Magnetic field increases (e.g.,Muslimov & Page 1996).

PSR J1734-3333 is associated with SNR G354.8-0.8





(From White \& Green , Astro.Astrophys. Supple. Ser.118. 329 .1996)

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Estimating diameter of G354.8-0.8

- Pavlovic et al (2014) present new empirical radio surface-brightness-to diameter ($\Sigma - D$) relations for supernova remnants (SNRs) in our Galaxy.

- They select calibrators from Greens SNR catalog (Green 2009) based on literature of `A Catalogue of Galactic supernova remnants (2009 March version).

For G354.8-0.8 Diameter = 34.8 pc, Distance =6.3 kpc from flux-density 2.8 Jy.

Estimating real age of G354.8-0.8

- ✓ **The evolution of a SNR : free-expansion, Sedov-Taylor (ST) and pressure -driven snowplow (PDS) .**

- ✓ **According the model of Cioffi (D.F. Cioffi , et al ApJ ,334, 252, 1988) , we derive an expression**

$$t \approx 1.0\times 10^{4}\cdot\left[\left(\frac{R_{PDS}}{14\mathrm{pc}}\right)^{10/3} E_{51}^{-20/21} n_0^{10/7} \xi_m^{-10/21} + \frac{1}{3}\right]\xi_m^{-5/14} E_{51}^{3/14} n_0^{-4/7}\ \mathrm{yrs} \qquad (3)$$

$$R_{SNR} \sim 17.4\ \mathrm{pc}, \qquad t_{SNR} \sim 23.8\ \mathrm{kyrs}$$

1) Low latitude , 2) Core-collapse supernova

ξ_m --Metallicity factor for solar abundance,s

$$n_0 \sim 1\ cm^{-3}, E \sim 1\times 10^{51}\ \mathrm{erg/s},\ \xi_m \sim 1;$$

n_0 Ambient hydrogen density

Spin-down evolution

If the dipole braking still dominates, and the magnetic field evolution can’t be ignored, Blandford \& Romani (1988) re-formulate the braking law of a pulsar as

$$\dot{\nu} = -\frac{8\pi^2 R^6 \sin^2\theta}{3c^3} B_{surf}^2(t)\nu^3 \quad (4)$$

Integraling Eq.(4) gives

$$\nu^{-2} = \nu_0^{-2} + 2\int_0^t \frac{8\pi^2 R^6 \sin^2\theta}{3Ic^3} B_{surf}^2(t)dt'$$

$$= \nu_0^{-2} + 2\int_0^t \frac{B_{surf}^2(t)}{(3.2\times 10^{19})^2}dt', \qquad (5)$$

where we assume $\mathrm{R} \sim 10^6\,\mathrm{cm},\ \sin^2\theta \sim 1,\ \text{and I}\sim 10^{45}\,\mathrm{g}\cdot\mathrm{cm}^2$

From Eq. (5) we get: $$P = P_0[1+2P_0^{-2}\int_0^t \frac{B_{surf}^2(t)}{(3.2\times 10^{19})^2}dt']^{1/2} \qquad (6)$$

Then we can represent the spin-down age of the star in the form:

$$\tau_c = \frac{-\nu}{2\dot{\nu}} = \frac{P}{2\dot{P}} = \frac{K}{B_{\mathrm{surf}}^2(t)}\int_0^t B_{\mathrm{surf}}^2(t)dt', \qquad (7)$$ where $\mathrm{K} = [1-(P_0/P)^2]^{-1}$

Spin-down evolution

Thus, assuming that in the saturation regime for PST J1734 3333,

$$B_{surf}(t) \propto t^{\varepsilon},$$

we obtain

$$\tau_c \sim \frac{K}{2\varepsilon + 1} t \qquad (8)$$

Combing with

$$n = 3 - 4\left(\frac{\dot{B}_{\mathrm{surf}}}{B_{\mathrm{surf}}}\right)\left(\frac{P}{2\dot{P}}\right) = 3 - 4\left(\frac{\dot{B}_{\mathrm{surf}}}{B_{\mathrm{surf}}}\right)\tau_c \qquad ,$$

we get

$$n \sim 3 - \frac{4\varepsilon K}{2\varepsilon + 1} \qquad (9),$$

Spin-down evolution

From Eq.(8) and Eq,(9) , we find that $K \sim \frac{3-n}{2} + \frac{\tau_c}{t}$ (10),

and $\varepsilon \sim \frac{3-n}{2(n-3+2K)}$ (11)

Inserting n=0.9(2) , $\tau_c = 8.13$ kys, and $B_{surf} = 5.22 \times 10^{13}$ G,

into Eqs.(8-10), we obtain

$$K = 1.39 \pm 0.10, \ \varepsilon = 1.53 \pm 0.17$$

Initial parameters

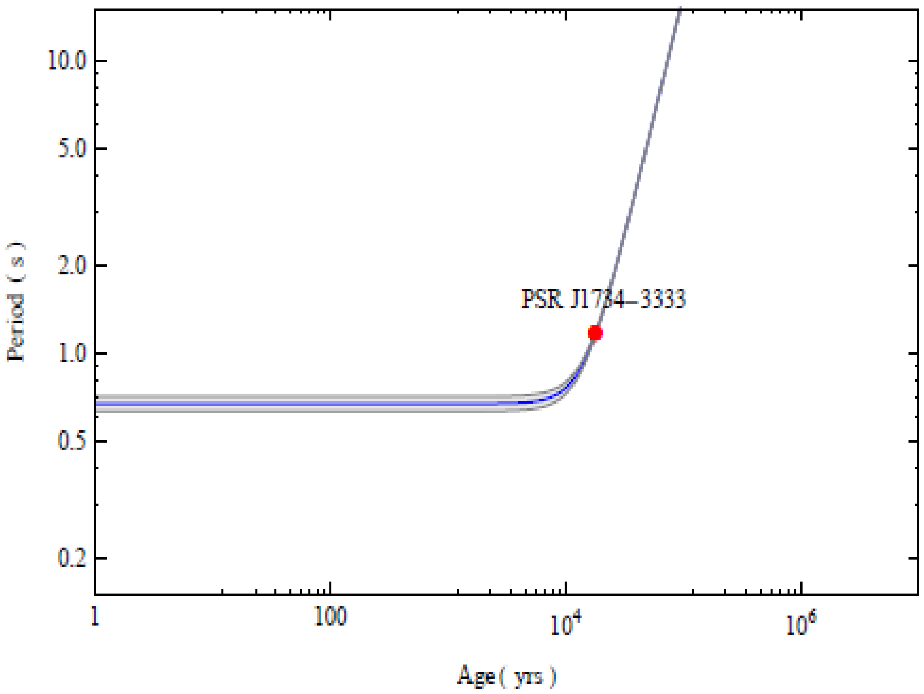
From $\mathrm{K} = [1 - (P_0 / P)^2]^{-1} \Rightarrow P_0 = P(1 - \frac{1}{K})^{1/2}$

we get the initial spin period $\mathrm{P}_0 \approx 0.619 \pm 0.051\ \mathrm{s},$

From $B_{surf}(t) = B_{surf}(0) \times (\frac{t}{1\mathrm{yr}})^{\varepsilon},$

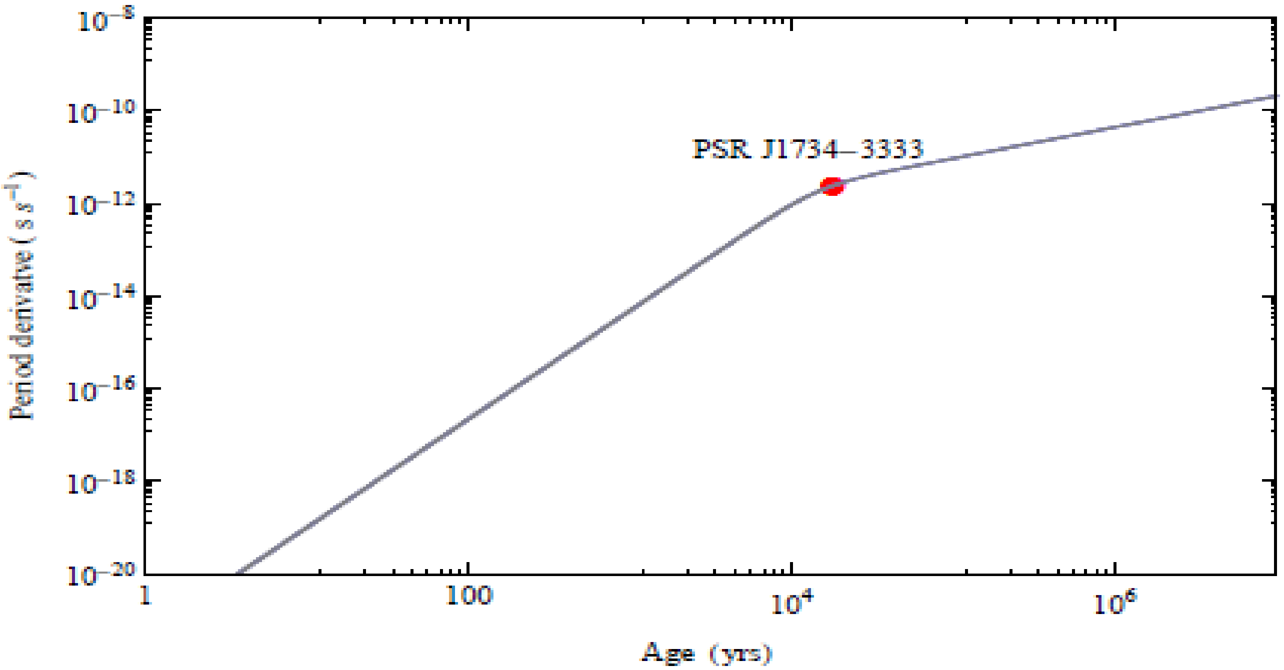
we get the initial surface magnetic field ,

$$B_{surf}(0) = (1.05 \pm 0.0008) \times 10^8\,\mathrm{G},$$



$$P = P_0[1 + 2P_0^{-2}\int_0^t \frac{B_{surf}^2(t)}{(3.2\times10^{19})^2}dt']^{1/2} \approx P_0[1 + \frac{2\cdot B_{surf}^2(0)\cdot(\frac{t}{\mathrm{yr}})^{2\varepsilon}}{P_0^2\cdot(3.2\times10^{19})^2(2\varepsilon+1)}\cdot(\mathrm{t}\times3.154\times10^7\ \mathrm{s})]^{1/2}$$

If the evolution time t~50 kyrs, $P \sim 5.3$ s t ≥ 100 kyrs, $P \geq 16.6$ s



$$\dot{\mathrm{P}}(\mathrm{t})=\frac{B_{surf}^2(t)}{(3.2\times10^{19})^2P(t)}\approx\frac{B_{surf}^2(0)\cdot(\frac{t}{\mathrm{yr}})^{2\varepsilon}}{P_0\cdot(3.2\times10^{19})^2}\cdot[1+\frac{2\cdot B_{surf}^2(0)\cdot(\frac{t}{\mathrm{yr}})^{2\varepsilon}}{P_0^2\cdot(3.2\times10^{19})^2(2\varepsilon+1)}\cdot(\mathrm{t}\times3.154\times10^7\ \mathrm{s})]^{-1/2}$$

For convenience, we denote $f(t)=[1+\frac{2\cdot B_{surf}^2(0)\cdot(\frac{t}{\mathrm{yr}})^{2\varepsilon}}{P_0^2\cdot(3.2\times10^{19})^2(2\varepsilon+1)}\cdot(\mathrm{t}\times3.154\times10^7\ \mathrm{s})]$

Spin-down evolution

In the early stage of field evolution, the pulsar appears older, $\tau_c >> t$, in the late evolution stage, the pulsar appears younger, $\tau_c < t$.

$$\tau_c = \frac{P}{2\dot{P}} = \frac{P_0^2 \cdot (3.2\times10^{19})^2}{2B_0^2 \cdot (\frac{t}{\text{yr}})^{2\varepsilon}} \cdot f(t) \quad \text{s}$$

$$= \frac{P_0^2 \cdot (3.2\times10^{19})^2}{2B_0^2 \cdot (\frac{t}{\text{yr}})^{2\varepsilon} \cdot 3.154\times10^7} \cdot f(t) \quad \text{yrs}$$

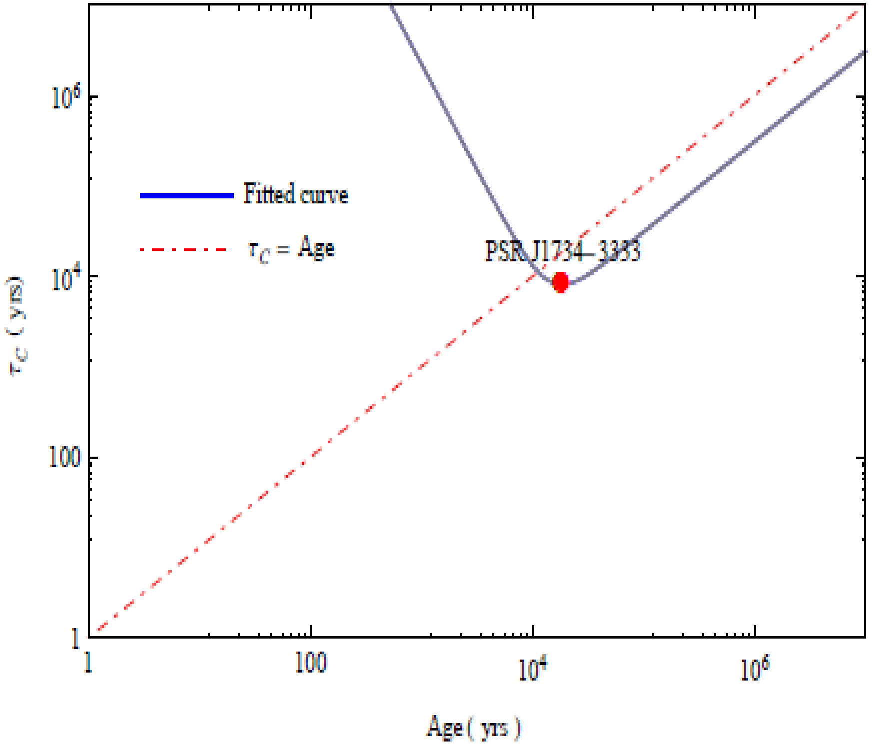


FIG. 3.— The characteristic age as a function of t for PSR J1734−3333. Here, the measured value of τ_c is shown with the red dot. The error in data-point is smaller than the size of the symbol.

Braking index evolution

- The increase of the dipole magnetic field causes a low braking index n < 3
- Braking index n increases (faster, then slower), and finally approaches a limited value n~1.625

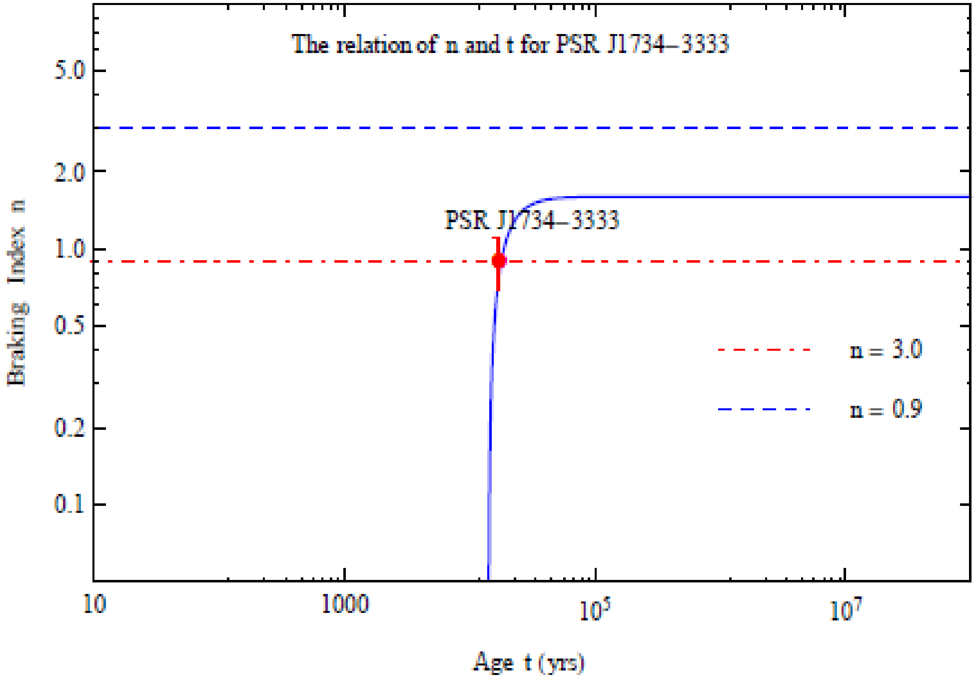
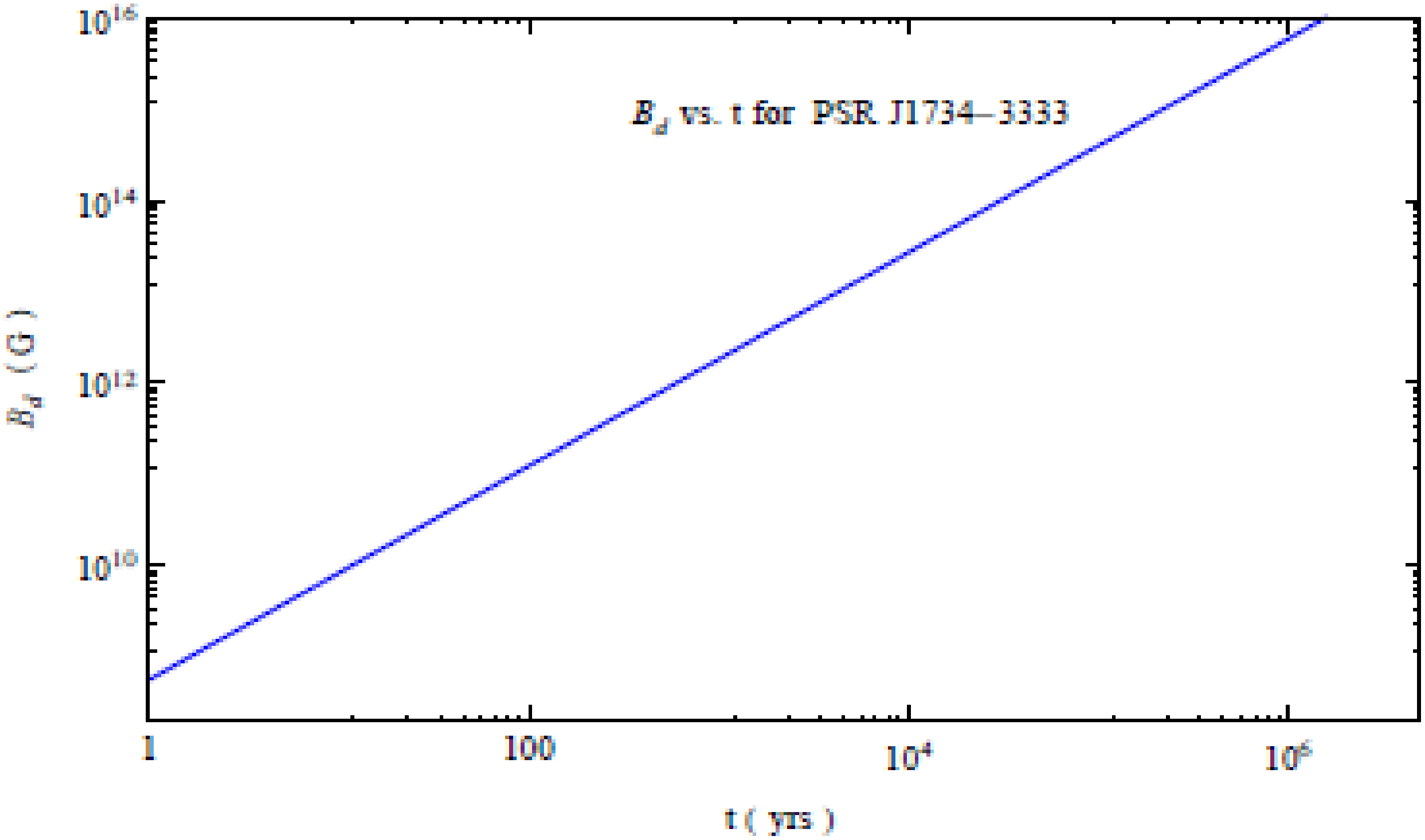
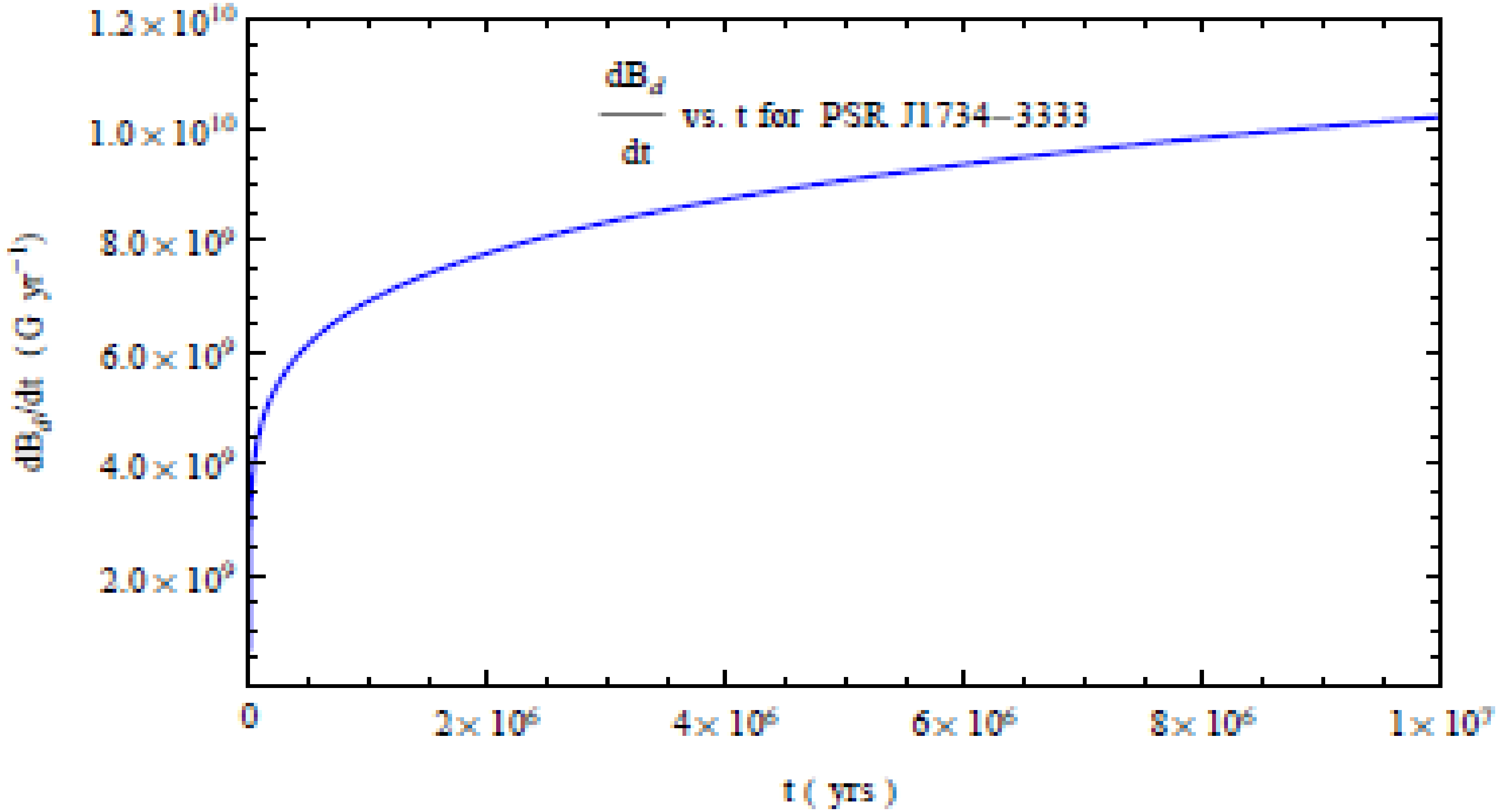


FIG. 1.— Braking index as a function of *t* for PSR J1640−4631.

$$n = 3 - \frac{4\varepsilon\tau_c}{t} \approx 3 - \frac{4\varepsilon}{t} \times \frac{P_0^2 \cdot (3.2\times10^{19})^2}{2B_0^2 \cdot (\frac{t}{\mathrm{yr}})^{2\varepsilon} \cdot (3.154\times10^7)} \cdot f(t)$$


B_d vs. t for PSR J1734−3333
10^{16}
10^{14}
10^{12}
10^{10}
B_d (G)
1
100
10^4
10^6
t (yrs)

(a)


$\frac{dB_d}{dt}$ vs. t for PSR J1734−3333
dB_d/dt (G yr^{-1})
1.2×10^{10}
1.0×10^{10}
8.0×10^{9}
6.0×10^{9}
4.0×10^{9}
2.0×10^{9}
0
2×10^{6}
4×10^{6}
6×10^{6}
8×10^{6}
1×10^{7}
t (yrs)

(b)

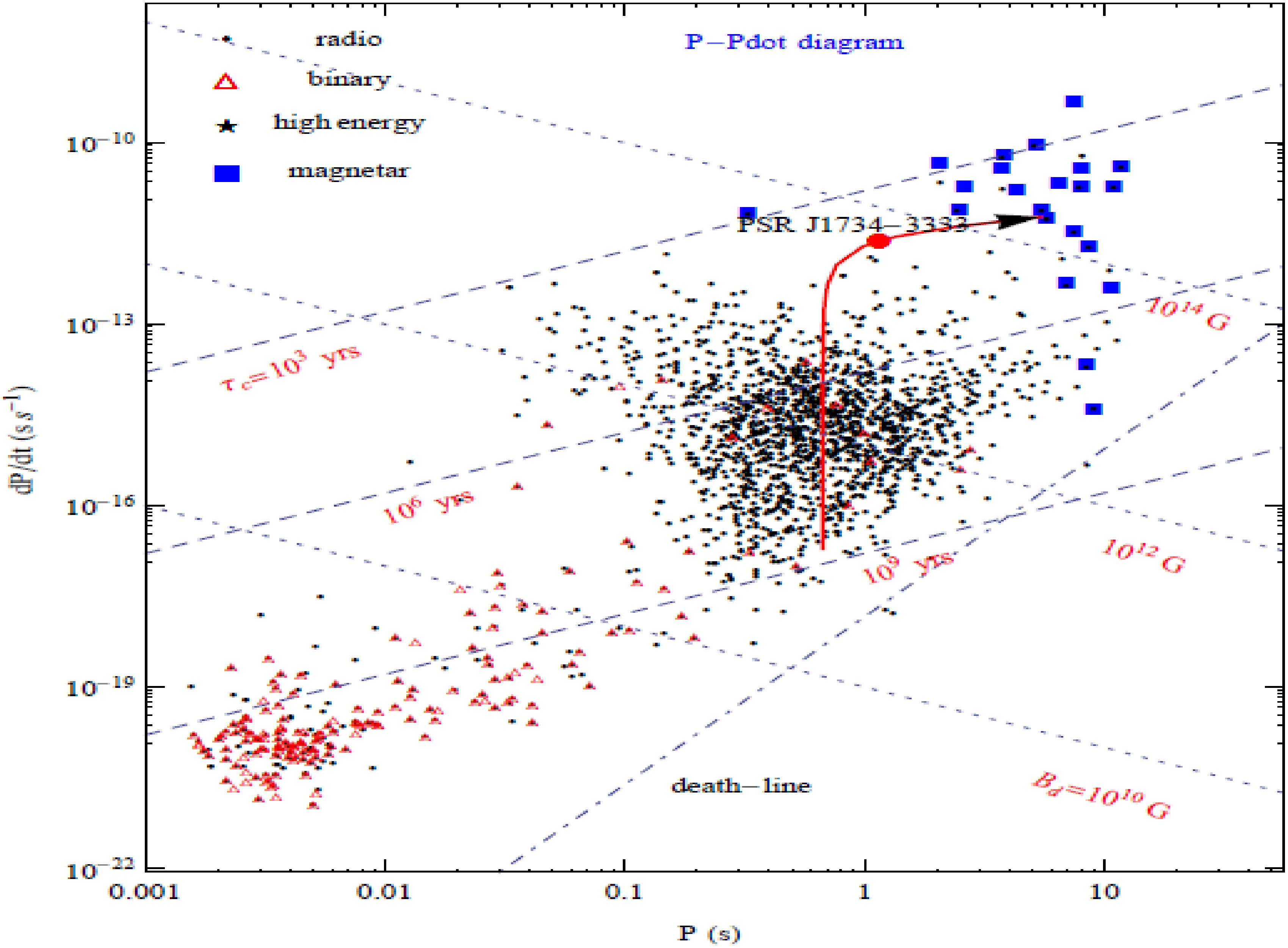


FIG. 6.— Long term rotational evolution of PSR J1734−3333 dominated by the dipole magnetic field increase. Radio, binary and magnetars are defined by black dot, red triangle, and blue square, respectively. The red solid circle is the observations of PSR J1734−3333.

Conclusions

In this work, we present a possible interpretation for very small braking index of PSR J1734-3333, which challenges the current theories of braking mechanisms in pulsars, and estimate some initial parameters. According to our suggestions, this pulsar could be born with a superhigh internal magnetic field ~ 10^14 -10^16 G, and could undergo a supercritical accretion soon after its formation in a supernova.

This strong magnetic field has been buried under the surface, and is relaxing out of the surface at present due to Ohmic diffusion. The increasing of surface dipole magnetic field results in the small braking index of 0.9. Keep the current field-growth index, the surface dipole field would reach a magnitude of 10^14 G within t ~50 kyrs, and would reach the maximum of the internal magnetic field strength in a few hundred kyrs , which implies that this pulsar is a potential magnetar.

Thank you very much!