For FPS6, Wuhan, 2017

Wind braking of pulsars: evolution of the braking index

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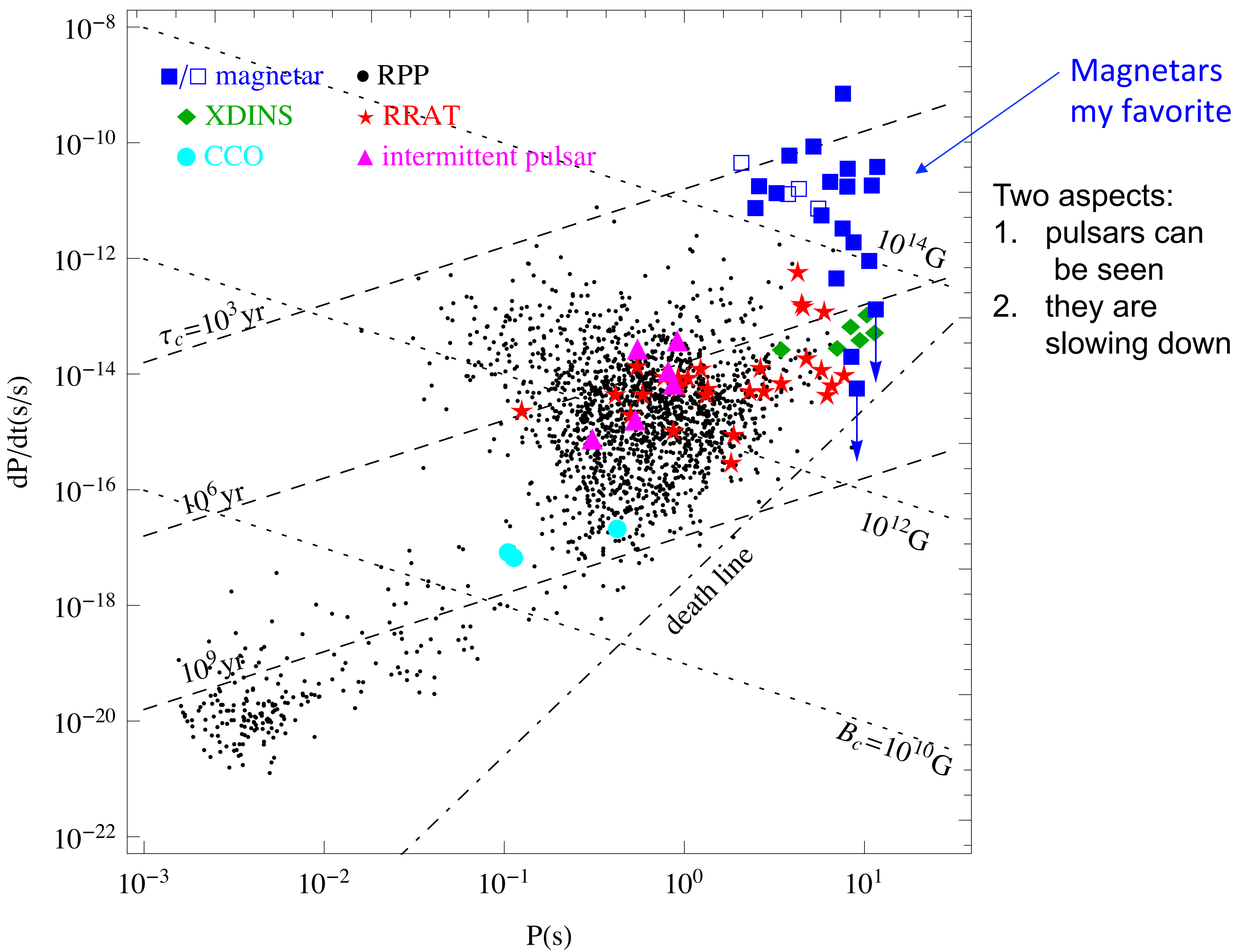
Content

1. Introduction: how do pulsars work?
2. Wind braking of pulsars (previous works):
   intermittent pulsars (Li+ 2014 ApJ),
   Crab+ (Kou+2015 MN),
   braking index & nu2dot (Ou+ 2016 MN),
   variable timing (Kou+ 2016 RAA)
3. Wind braking of pulsars: braking index evolution (Tong & Kou 2017 ApJ)
4. Summary and prospects



Two aspects:

1. pulsars can be seen
2. they are slowing down

updated from Tong 2016

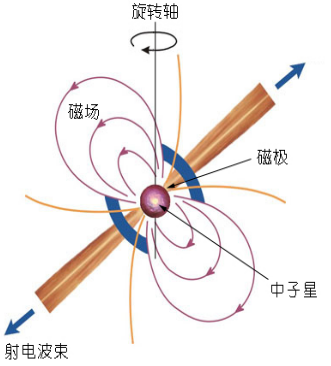
How do pulsars work?

magnetosphere:

1. Rotating dipole in vacuum: no particles
2. Plasma filled magnetosphere (GJ 1969): no particle acceleration
3. plasma filled magnetosphere+ dipole field line geometry+ acceleration gaps
4. various versions of MHD, PIC simulations

braking mechanism:

1. Magnetic dipole radiation
2. Free flow, ideal MHD
3. current loss, wind braking …
4. MHD …

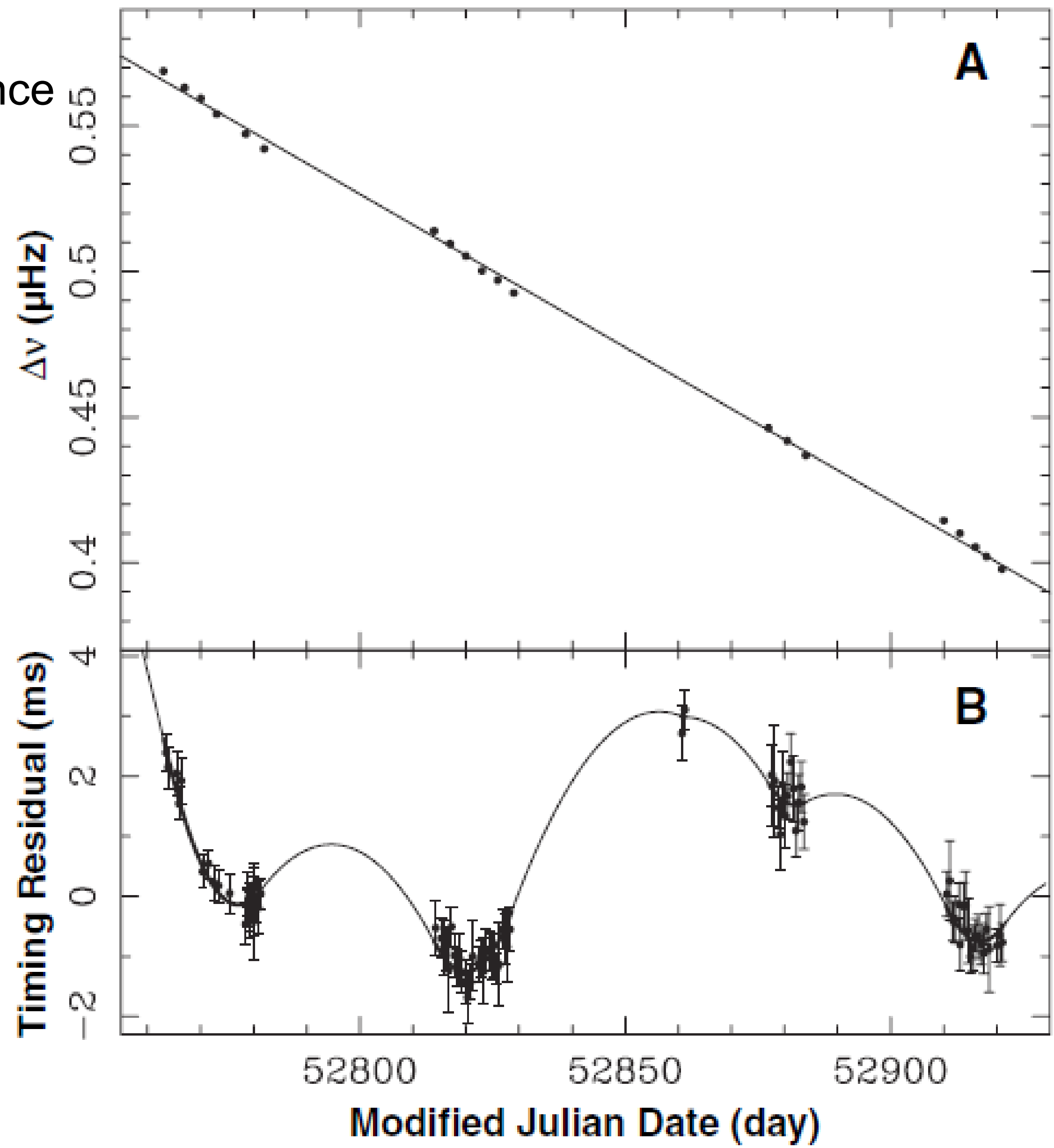


Wind braking of pulsars

- an oblique rotating dipole
- focused on braking mechanism
- perpendicular component: approximated by magnetic dipole radiation
- parallel component: responsible for particle acceleration (Ruderman & Sutherland 1975 etc)
- spin-down torque (Xu & Qiao 2001; ⋯):

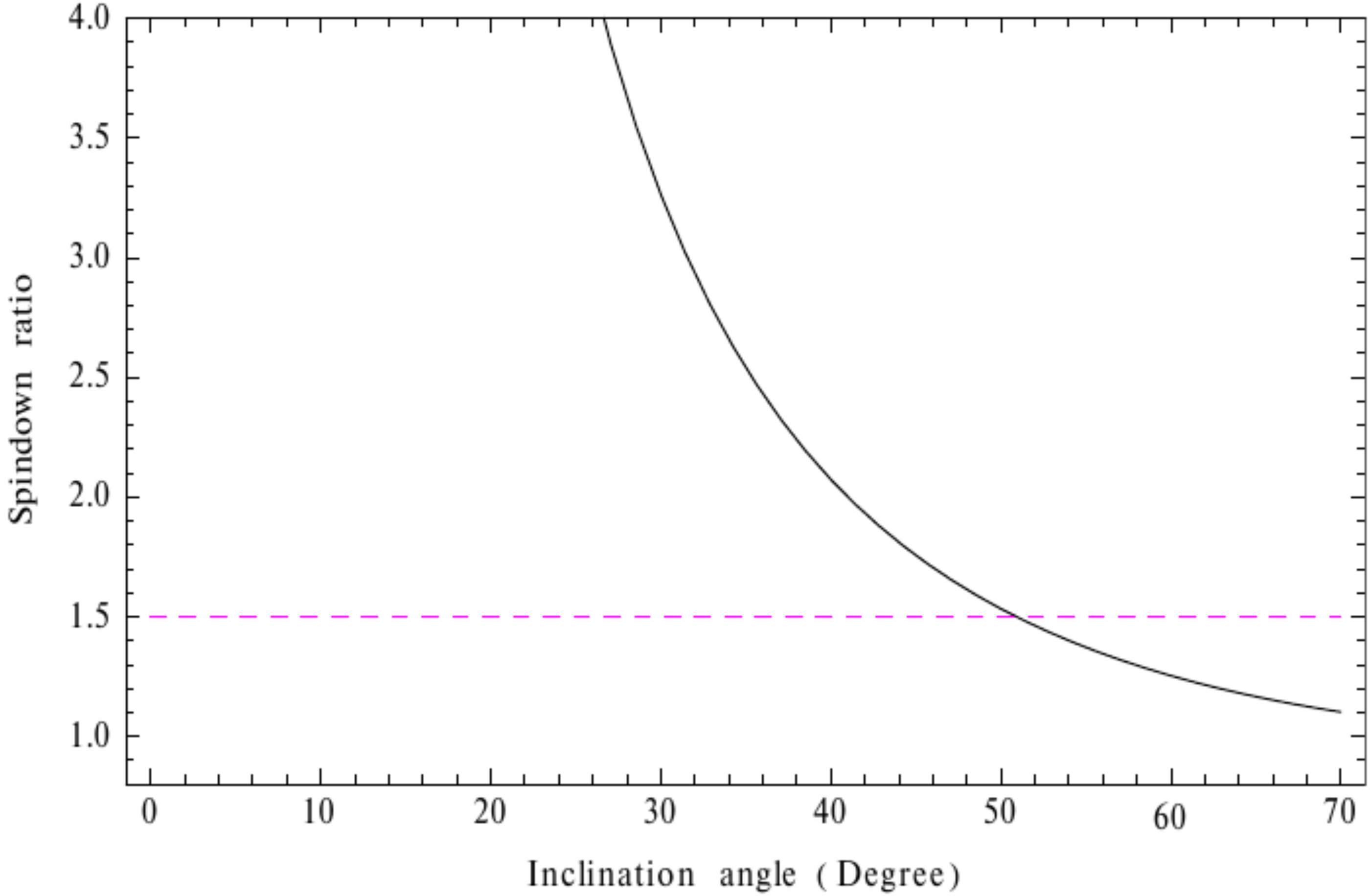
$$I\frac{d\Omega}{dt} = -\frac{2\mu^2\Omega^3}{3c^3}(\sin^2\alpha + 3\kappa\frac{\Delta\phi}{\Delta\Phi}) \equiv -\frac{2\mu^2\Omega^3}{3c^3}\eta$$

Intermittent pulsars B1931+24
(Kramer+ 2006):
observations for the existence of a particle wind



1st work

Wind braking model for the spin down behavior of intermittent pulsars
Li, Tong et al. 2014, ApJ

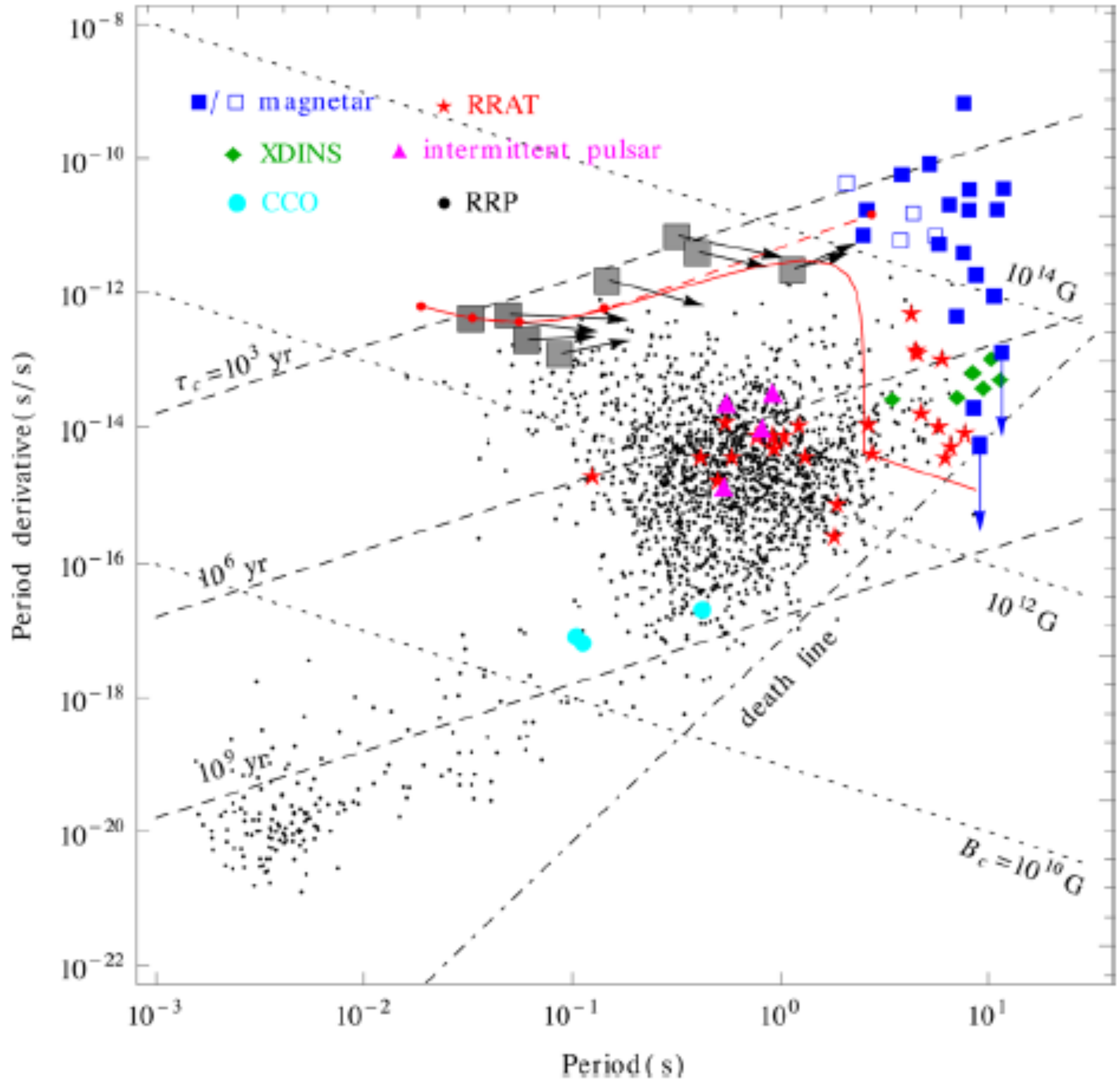


2nd work

Improving the wind braking model

- Inconsistencies in the original wind braking model
- Improvements (Kou & Tong 2015):
  1. Particle density (consistent with inclination angle observations)
  2. Pulsar death (long term evolution)

Evolution of pulsars on the P-Pdot diagram (for the Crab pulsar)
Kou & Tong 2015 MN



Definition of braking index n (Livingstone+ 2005b)

- Power law spindown of pulsars

$$\dot{\nu} = -K\nu^n, \tag{1}$$

- Braking index

$$n = \frac{\nu\ddot{\nu}}{\dot{\nu}^2}. \tag{2}$$

- Second braking index

$$m = \frac{\nu^2\dddot{\nu}}{\dot{\nu}^3}.$$

Summary (2015): 8 sources

1. B0531+21 (Crab, Lyne+1993; 2015): n=2.51(1)
2. B0540-69 (Livingstone+2005a; Ferdman+ 2015): 2.140(9)
3. J1833-1034 (Roy+ 2012): 1.8569(6)
4. B0833-45 (Vela, Lyne+1996): 1.4(2)
5. B1509-58 (Livingstone+2005b; Livingstone & Kaspi 2011): 2.839(3)
6. J1846-0258 (Livingstone+2006): 2.65(1)
7. J1119-6127 (Weltevrede+2011): 2.684(2)
8. J1734-3333 (Espinoza+2011): 0.9(2)

in order of increasing period

Observational progresses (1)

1. high braking index n=3.15(3) (Archibald et al. 2016a)
2. Variable (smaller) braking index of J1846 (Archibald et al. 2015)
3. Two braking indices in two states of B0540 (Marshall et al. 2016)
4. Magnetar-like outburst from J1119 (Archibald et al. 2016b)

- Pulsar braking studies has entered a new era

3rd -5th works

Subsequent works

- braking index of 8 pulsars, nu2dot of 222 pulsars and 15 magnetars (Ou, Tong+ 2016 MN)
- short term variation: variable spin-down rate and variable braking index (Kou+ 2016 RAA)
- long term evolution of braking index (Tong & Kou 2017 ApJ)

Open questions

1. how to explain the braking index larger than 3 and smaller than 3?
2. inclination angle evolution in the wind braking model?

- →Answer: by including inclination angle evolution in the wind braking model, both braking index larger than 3 and smaller than 3 can be explain

Coupled evolution of rotation and inclination in the wind braking model

- Spin-down:

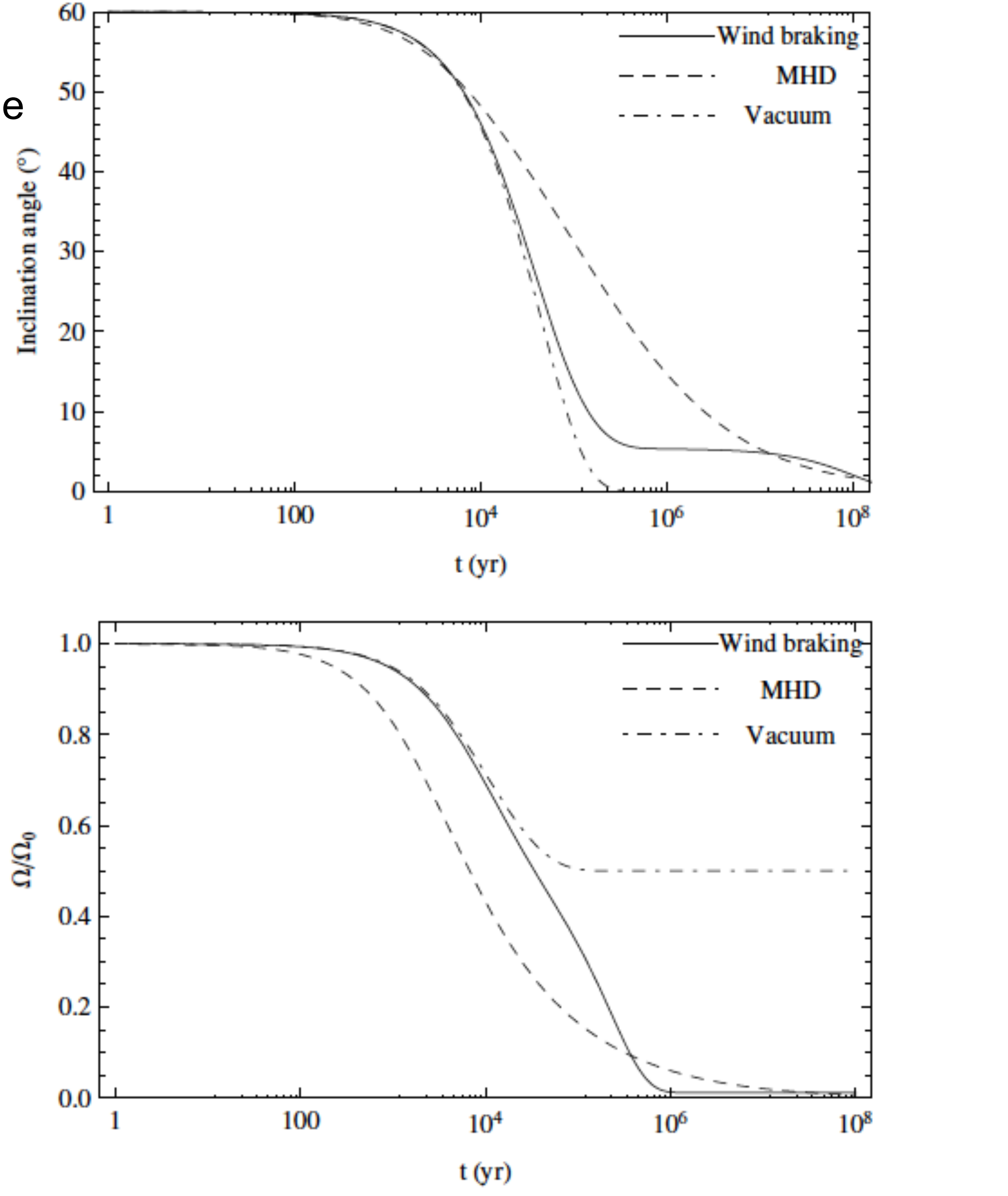
$$I\frac{d\Omega}{dt} = -\frac{2\mu^2\Omega^3}{3c^3}(\sin^2\alpha + 3\kappa\frac{\Delta\phi}{\Delta\Phi}) \equiv -\frac{2\mu^2\Omega^3}{3c^3}\eta,$$

- Alignment: $$I\Omega\frac{d\alpha}{dt} = -\frac{2\mu^2\Omega^3}{3c^3}\sin\alpha\cos\alpha.$$

originates from the general equation of motion:
in analogy with MHD treatment
(Philippov et al. 2014)

$$I\frac{d\mathbf{\Omega}}{dt} = \boldsymbol{K},$$

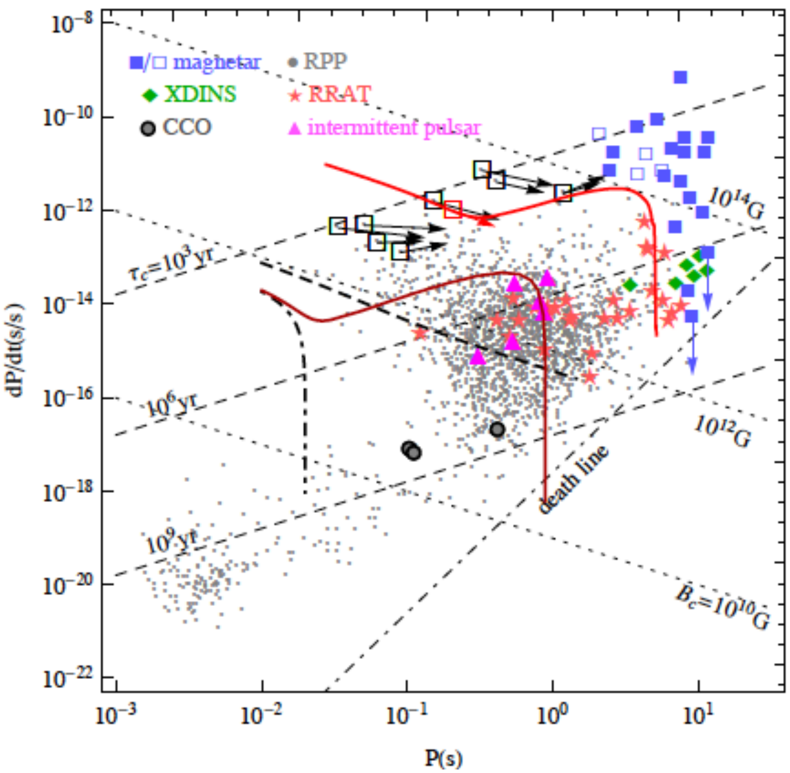
Rotation and inclination angle evolution
Tong & Kou 2017 ApJ

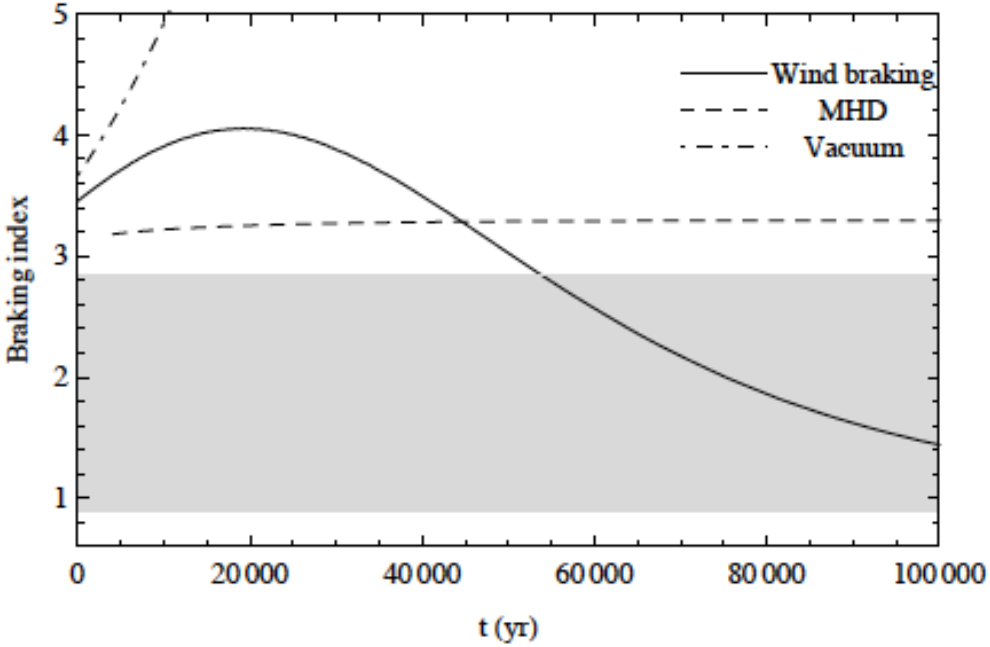


unification in the wind braking model: evolution of n from larger than 3 to about 1

From Crab-like to Vela-like

Tong & Kou 2017





Observational progresses (2)

1. braking index of a radio quiet gamma-ray pulsar ($n=2.598$, Clark et al. 2016)
2. braking index of two Vela-like pulsars ($n<=2$, Espinoza et al. 2016)

- During the reviewing process, we saw these two observations. Both are consistent with predictions of the wind braking model: evolution from the Crab-like case to the Vela-like case

Comments

- Simple assumptions, so many results
- Therefore
  1. Must be wrong: some fundamental, principle, and naïve errors (MN referee)
  2. Too simple to be true: should be as complicated as the MHD simulations, at least (ApJ referee)
  3. The particle component is the key input (Tong)

Wind braking of pulsars: summary

1. **variable spin-down states of intermittent pulsars (Li+ 2014): predicting the inclination angle and braking index of intermittent pulsars**
2. **dipole+wind: resulting in $1<n<3$ (Kou & Tong 2015)**
3. two states of B0540: similar to intermittent pulsars (Kou et al. 2016), predicted a smaller braking index, not as small as later observed (may involve an increasing particle density, as that of J1846)
4. smaller braking index of J1846: similar to Crab (Kou et al. 2016), increasing particle density →smaller braking index
5. $n>3$ for J1640: decreasing inclination angle at the early time→braking index larger than 3, predicting long term evolution of pulsar braking index from larger than 3 to about 1 (from Crab-like to Vela-like) (Tong & Kou 2017)
6. unification of braking index and nu2dot observations: Ou et al. (2016)

- steady state for most sources; long term evolution; short term evolution (different spin-down states; an increasing particle density, hard to verify or falsify)
- B0540 as the touchstone