PULSAR WIND MODEL FOR THE SPIN-DOWN BEHAVIOR OF INTERMITTENT PULSARS

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ABSTRACT

Intermittent pulsars are part-time radio pulsars. They have higher slow down rates in the on state (radio-loud) than in the off state (radio-quiet). This gives evidence that particle wind may play an important role in pulsar spindown. The effect of particle acceleration is included in modeling the rotational energy loss rate of the neutron star. Applying the pulsar wind model to the three intermittent pulsars (PSR B1931+24, PSR J1841−0500, and PSR J1832+0029) allows their magnetic fields and inclination angles to be calculated simultaneously. The theoretical braking indices of intermittent pulsars are also given. In the pulsar wind model, the density of the particle wind can always be the Goldreich–Julian density. This may ensure that different on states of intermittent pulsars are stable. The duty cycle of particle wind can be determined from timing observations. It is consistent with the duty cycle of the on state. Inclination angle and braking index observations of intermittent pulsars may help to test different models of particle acceleration. At present, the inverse Compton scattering induced space charge limited flow with field saturation model can be ruled out.

Key words: pulsars: individual (PSR B1931+24, PSR J1832+0029, PSR J1841−0500) – stars: neutron – stars: winds, outflows

Online-only material: color figure

1. INTRODUCTION

Intermittent pulsars are a special class of part-time radio pulsars (Kramer et al. 2006; McLaughlin et al. 2006; Camilo et al. 2006; Wang et al. 2007). Their nulling timescales are very long compared with that in ordinary pulsars (Wang et al. 2007). They emit radiation switching between the on state and the off state. PSR B1931+24 (the first intermittent pulsar; Kramer et al. 2006) exhibits the alternation of the on state (5–10 days) and the off state (25–35 days), which is about 38 day quasi-periodicity (Young et al. 2013). Thereafter, Camilo et al. (2012) and Lorimer et al. (2012) successively presented the extraordinary long-term off state of PSR J1841−0500 and PSR J1832+0029 between their respective on states. More significantly, the spindown rate of the intermittent pulsar during the on state is larger than that during the off state. For PSR B1931+24, it enhances ~50% during its on state compared to its off state. For PSR J1841−0500 and PSR J1832+0029, the enhancement is around 150% and 77%, respectively.

Many scenarios have been proposed for intermittent pulsars (mainly centered on PSR B1931+24), e.g., pulsars with orbiting objects (Li 2006), reactivated dead pulsars or nulling pulsars viewed from the opposite direction (Zhang et al. 2007), non-radial oscillation (Rosen et al. 2011), and precession (Jones 2012). However, it is still unknown what is account for the on/off transition and why the rotation slows down faster when the pulsar is on than when it is off.

An effective model is that an additional particle flow slows down the rotation when the pulsar is on (Kramer et al. 2006). A magnetospheric model is presented by Li et al. (2012b) for the spindown of intermittent pulsars. However, the particle acceleration is not considered in these models (the magnetospheric model considered the particle acceleration by introducing a finite conductivity). Particle acceleration is crucial for the generation of pulsar radio (and high energy) emission. The pulsar wind model of Xu & Qiao (2001) considered the effect of particle wind plus magnetic dipole braking. Different particle acceleration models are considered in that paper. This pulsar wind model is applied to the three intermittent pulsars, i.e., PSR B1931+24, PSR J1841−0500, and PSR J1832+0029. The spindown ratio between the on and off states depends on the particle acceleration potential and the magnetic inclination angle. The magnetic field and inclination angle of each source are calculated in different acceleration potentials. Meanwhile, their theoretical braking indices are also shown.

The rotational energy loss rate in the presence of a particle wind is calculated in Section 2. Applying the pulsar wind model to intermittent pulsars is given in Section 3. Discussions and conclusions are presented in Section 4.

2. ROTATIONAL ENERGY LOSS RATE IN THE PRESENCE OF A PARTICLE WIND

Pulsars may be viewed as an oblique rotating dipole. The magnetic moment has both a parallel component and a perpendicular component relative to the rotation axis. The rotational energy loss rate due to the perpendicular magnetic moment may be approximated by the magnetic dipole braking (Shapiro & Teukolsky 1983)

\[ \dot{E}_d = \frac{2 \mu^2 \Omega^4}{3c^3} \sin^2 \alpha, \]

where \( \mu \) is the magnetic dipole moment, \( \Omega \) is the angular rotation rate of the neutron star, \( c \) is the speed of light, and \( \alpha \) is the angle between the rotation axis and the magnetic axis (i.e., magnetic inclination angle). The effect of the parallel magnetic moment is associated with particle acceleration (e.g.,

6 This component may actually be some form of particle outflow.
The rotational energy loss rate due to this component may be written as (i.e., particle wind; Xu & Qiao 2001)

$$E_p = 2\pi r_p^2 c \rho \Delta \Phi,$$

(2)

where $r_p$ is the polar cap radius, $\rho$ is the charge density in the acceleration region, and $\Delta \Phi$ is the corresponding acceleration potential. The polar cap radius is $r_p = R(RQ/c)^{1/2}$ (where $R$ is the neutron star radius) if the large-scale magnetic field geometry is of the dipole forms. Observationally, the different on states of intermittent pulsars are quite stable (i.e., no significant variations between different states; Lorimer et al. 2012; Young et al. 2013). One way to achieve this is that the charge density in the acceleration region is always the same.\(^7\) The most natural value for the charge density is the Goldreich–Julian density (Goldreich & Julian 1969). Therefore, we chose $\rho = \rho_{GJ} = \Omega B/(2\pi c)$, where $B$ is the polar magnetic field. The parallel magnetic field is related to the magnetic moment as $\mu = 1/2BR^3$ (Shapiro & Teukolsky 1983). The presence of the acceleration potential can accelerate primary particles. Secondary particles are generated subsequently.\(^5\) These particles are responsible for the radio (and high-energy) emissions of pulsars. Meanwhile, they will also contribute to the rotational energy loss rate of the central neutron star. There are various proposals for the acceleration potential (see Xu & Qiao 2001, and references therein). Different acceleration potential results in different rotational energy loss rates. Therefore, pulsar timing observations can be employed to distinguish between different particle acceleration models.

The maximum acceleration potential for a rotating dipole is (Ruderman & Sutherland 1975) $\Delta \Phi = \mu \Omega^2/c^2$. The rotational energy loss rate due to the particle wind can be rewritten as

$$E_p = \frac{2\mu^2 \Omega^4}{3c^3} \left( \sin^2 \alpha + 3 \frac{\Delta \Phi}{\Delta \Phi} \right),$$

(3)

The total rotational energy-loss rate is the combination of the perpendicular component and the parallel component. Assuming that the magnetic dipole component and the particle wind component contribute independently, the total rotational energy loss rate is

$$E = E_d + E_p = \frac{2\mu^2 \Omega^4}{3c^3} \left( \sin^2 \alpha + \frac{3 \Delta \Phi}{\Delta \Phi} \right),$$

Case II. (4)

Note that the particle component may be mainly related to the parallel magnetic moment. The parallel magnetic moment is $\mu_\parallel = \mu \cos \alpha$. Taking this point into consideration, the corresponding rotational energy loss rate is (Xu & Qiao 2001)

$$E = \frac{2\mu^2 \Omega^4}{3c^3} \left( \sin^2 \alpha + 3 \frac{\Delta \Phi}{\Delta \Phi} \cos^2 \alpha \right),$$

Case I. (5)

The above two cases are called case I and case II, respectively (according to the time order when they first appear in literature). Case I was originally considered by Xu & Qiao (2001). A similar expression was also obtained by Contopoulos & Spitkovsky (2006). Case II is also possible considering recent numerical simulations (Spitkovsky 2006; Li et al. 2012a). These two cases only differ by a factor of $\cos^2 \alpha$.\(^7\) Other more complicated/more interesting possibilities are also possible.\(^8\) The density of secondary particles can be much higher than the Goldreich–Julian density, since they can have a much larger multiplicity.

Table 1

| No. | Acceleration Model          | $\eta$ |
|-----|----------------------------|--------|
| 1   | VG (CR)                    | \sin^2 \alpha + 4.96 \times 10^2 B_{12}^{-3/7} \Omega^{-15/7} \cos^2 \alpha |
| 2   | VG (ICS)                   | \sin^2 \alpha + 1.02 \times 10^2 B_{12}^{-2/7} \Omega^{-13/7} \cos^2 \alpha |
| 3   | SCLF (I,CR)                | \sin^2 \alpha + 38B_{12}^{-1/7} \cos^2 \alpha |
| 4   | SCLF (II, ICS)             | \sin^2 \alpha + 2.3B_{12}^{-2/11} \Omega^{-3/13} \cos^2 \alpha |
| 5   | SCLF (I)\(^a\)            | \sin^2 \alpha + 9.8 \times 10^2 B_{12}^{-3/7} \Omega^{-15/7} \cos^2 \alpha |
| 6   | OG\(^b\)                  | \sin^2 \alpha + 2.25 \times 10^2 B_{12}^{-3/7} \Omega^{-3/7} \cos^2 \alpha |
| 7   | CAP\(^c\)                 | \sin^2 \alpha + 54B_{12}^{-1} \Omega^{-2} \cos^2 \alpha |

Notes: The neutron star radius is taken as $10^6$ cm.

\(^{a}\) A factor $10^2$ is missed in Xu & Qiao (2001).

\(^{b}\) Considering the modification due to Wu et al. (2003).

\(^{c}\) The case of constant acceleration potential (CAP; Yue et al. 2007). The gap potential is assumed to be $\Delta \phi = 3 \times 10^{12}$ V.

The total rotational energy loss rate in the presence of a particle wind can be rewritten as (Xu & Qiao 2001)

$$E = \frac{2\mu^2 \Omega^4}{3c^3} \eta,$$

(6)

with $\eta = \sin^2 \alpha + 3 \Delta \phi/\Delta \Phi \cos^2 \alpha$ (case I). Given the acceleration potential $\Delta \phi/\Delta \Phi$ and the rotational energy loss rate are known. The simplest case may be a constant acceleration potential (CAP; Yue et al. 2007). If the acceleration potential $\Delta \phi = 3 \times 10^{12}$ V, then $\eta = \sin^2 \alpha + 54B_{12}^{-1} \Omega^{-2} \cos^2 \alpha$ (where $B_{12}$ is polar magnetic field in units of $10^{12}$ G). Various physically motivated particle acceleration models have been proposed since Ruderman & Sutherland (1975). The expressions of $\eta$ for various acceleration models are listed in Table 1. The corresponding expression for case II can be obtained by dropping the factor $\cos^2 \alpha$. Xu & Qiao (2001) described six pulsar emission models, i.e., two vacuum gap (VG) models, three space charge limited flow (SCLF) models, and the outer gap (OG) model. In the VG model (Ruderman & Sutherland 1975), the situation in which primary electrons emit $\gamma$-rays via curvature radiation is called CR-induced and the situation in which primary electrons emit $\gamma$-rays via resonant inverse Compton scattering off the thermal photons (e.g., Zhang et al. 2000) is called ICS-induced. For the SCLF model (e.g., Arons & Scharlemann 1979; Harding & Muslimov 1998), regimes I and II are considered, which are, respectively, defined as the extreme cases without or with field saturation. Three models are included, i.e., the CR-induced SCLF model in regime II, the ICS-induced SCLF model in regime II, and the SCLF model in regime I. The potential drop, which is model-dependent, is different in each model, and so is the $\eta$-value. The following calculations will be mainly for case I. The calculation in case II is similar and will be discussed later.

3. **Pulsar Wind Model for the Spindown Behavior of Intermittent Pulsars**

3.1. Modeling Intermittent Pulsar On and Off State

If the on and off states of intermittent pulsars are solely due to a different geometry, then it may be difficult to explain the enhanced spindown during the on state. A particle wind can contribute to both the radio emission and rotational energy loss of the neutron star. Then, it seems possible that, compared with the off state, there is an additional particle wind during the on state.
state of the intermittent pulsar. A natural value for the density of this additional particle component is the Goldreich–Julian density (Goldreich & Julian 1969). During the off state, there should also be some amount of particle outflow. However, these particles failed somewhere during the acceleration and subsequent radiation process. Therefore, there is no radio emission detected during the off state (Lorimer et al. 2012). The rotational energy loss rate due to the off state particle component must be smaller than that due to the on state particle component. If the contribution from the off state particle component is small compared with the dipole radiation term, then magnetic dipole radiation will dominate the rotational energy loss rate in the off state of intermittent pulsars (Kramer et al. 2006).

If the off state magnetosphere of the intermittent pulsar is similar to the magnetosphere of the pulsar in the death valley, the magnetic dipole approximation may be valid. Previous studies showed that as the pulsar ages, the particle wind contribution to the rotational energy loss rate will gradually disappear (Contopoulos & Spitkovsky 2006; Tong & Xu 2012). When the pulsar passes through the death line, the remaining rotational energy loss rate is identical to that of the characteristic magnetic dipole radiation (e.g., proportional to \( \sin^2 \alpha \)). Numerical simulations are consistent with the analytical treatment (Li et al. 2012a). However, it is also possible that the off state magnetosphere of the intermittent pulsar is only a temporal failure (e.g., failure for one month or one year). In this case, it may be different from the magnetosphere of dead pulsars. X-ray observations during the off state may tell us some details of this particle component (Lorimer et al. 2012; with negative results, future observations will be more promising).

3.2. Calculations in Case I (Equation (5))

The origin of both dipole radiation and particle wind is from the star’s rotational energy: \( \dot{E} = -I\dot{\Omega} \) (\( I \) is the moment of inertia, Lorimer & Kramer 2005). From previous discussions, the spindown rate of the intermittent pulsars during the on and off states are, respectively,

\[ \dot{E} = -I\dot{\Omega}_{\text{on}} \]

\[ \dot{E}_{\text{off}} = -I\dot{\Omega}_{\text{off}}. \]

The above equation can be rewritten as

\[ \dot{\Omega}_{\text{on}} = -\frac{2\mu^2}{3Ic^3}\Omega^3 \eta, \]

\[ \dot{\Omega}_{\text{off}} = -\frac{2\mu^2}{3Ic^3}\Omega^3 \sin^2 \alpha. \]

Equation (10) can be rewritten as (assuming a moment of inertial of \( 10^{45} \text{g cm}^2 \))

\[ B \sin \alpha = 6.4 \times 10^{-19} \sqrt{P\dot{P}_{\text{off}}} \equiv B_c, \]

where \( P \) is the pulsar period, \( \dot{P}_{\text{off}} \) is period derivative during the off state, and \( B_c \) is defined as the characteristic magnetic field. If the characteristic magnetic field is taken as the star’s true magnetic field, this corresponds to an inclination angle \( \alpha = 90^\circ \) (Kramer et al. 2006). However, in the general case, the magnetic field and the inclination angle should be solved simultaneously. This can be achieved for intermittent pulsars since their spindown ratio during the on and off states can be measured. Dividing Equation (9) by Equation (10), the spindown ratio of intermittent pulsars between the on and the off states is

\[ r \equiv \frac{\dot{\Omega}_{\text{on}}}{\dot{\Omega}_{\text{off}}} = \frac{\eta}{\sin^2 \alpha} = \frac{\sin^2 \alpha + 3(\Delta \phi/\Delta \Phi) \cos^2 \alpha}{\sin^2 \alpha}. \]

Solving Equations (11) and (12) simultaneously, using the \( \eta \) values listed in Table 1, the resulting magnetic inclination angles for each intermittent pulsar in different acceleration models are listed in Table 2. The corresponding polar magnetic field can be directly obtained once the magnetic inclination angle is known: \( B = B_c/\sin \alpha \) (from Equation (11)). No solution exists for SCLF (II, ICS), since the corresponding magnetic inclination is very small and the polar magnetic field is too high to be physically acceptable (it is in the magnetar range). From the expression of \( \eta \), for a specific inclination angle \( \alpha \), \( \pi - \alpha \) gives the same result. Table 2 only shows the case of \( \alpha < 90^\circ \).

The calculation of the braking index \( n \equiv (\Omega/\dot{\Omega})^2 \) for intermittent pulsars is also straightforward. From Equation (10), the braking index during the off state is exactly three, if the moment of inertia, magnetic moment, and inclination angle are constant. However, from Equation (9) the braking index during the on state depends on the form of the acceleration potential. By differentiating Equation (9), the corresponding braking index is (Xu & Qiao 2001)

\[ n = 3 + \frac{\partial n}{\partial \Omega}. \]

The general expression for \( \eta \) is \( \eta = \sin^2 \alpha + k\Omega^{-a} B_{12}^{-b} \) (see Table 1, where \( k \) is constant). Therefore, the braking index for intermittent pulsars during the on state is

\[ n_{\text{on}} = 3 - \frac{r}{r - 1} - a. \]

It only depends on the spindown ratio and the coefficient \( a \) (\( a \) is determined by the acceleration potential dependence on \( \Omega \)). Acceleration potentials with the same \( \Omega \) dependence will have the same braking index. The braking index is not dependent on the different combinations of magnetic dipole radiation and particle wind. Therefore, the braking index is the same for case I and case II. The on state braking indices for the current three intermittent pulsars are shown in Table 3. The minimum braking

| Pulsar Name | VG(CR) | VG(ICS) | SCLF(II, CR) | SCLF(II, ICS) | SCLF(I) | OG | CAP |
|------------|--------|---------|-------------|---------------|--------|----|-----|
| B1931+24   | 51     | 80      | 22          | ...           | 62     | 75 | 19  |
| J1841−0500 | 24     | 53      | 6.7         | ...           | 38     | 60 | 6   |
| J1832+0029 | 53     | 87      | 24          | ...           | 63     | 76 | 19  |

Note: No solution exists for SCLF (II, ICS).
index for each acceleration model is also shown. The SCLF (II, ICS) model has a minimum braking index of 2.4, while the observed minimum braking index of pulsars is 0.9 ± 0.2 (Espinoza et al. 2011). Therefore, from the point of view of the braking index, the SCLF (II, ICS) model can also be ruled out.

Figures 1 and 2 separately show the spindown ratio and the braking index of PSR B1931+24 as a function of inclination angle in the vacuum gap model induced by curvature radiation. The dashed line is the observed spindown ratio of PSR B1931+24 (Kramer et al. 2006).

3.3. Discussions of Case II (Equation (4))

Case II differs from case I quantitatively. When obtaining the spindown ratio of intermittent pulsars (Equation (12)), many unknown factors are concealed (e.g., the moment of inertia, the magnetic dipole moment), and the observed spindown ratio is just a factor of two (from 1.5 to 2.5). Therefore, in modeling the spindown ratio of intermittent pulsars, the rotational energy loss rate must be accurate within a factor of two (relative to magnetic dipole braking case). For case II, Equation (11) is still valid. The expression for the spindown ratio in case II is

$$r \equiv \frac{\Omega_{\text{on}}}{\Omega_{\text{off}}} = \frac{\eta}{\sin^2 \alpha} = \frac{\sin^2 \alpha + 3\Delta \phi / \Delta \Phi}{\sin^2 \alpha},$$

(15)

Generally, \( \eta = \sin^2 \alpha + k \Omega^{-a} B_{c12}^{-b} \) (see Table 1. For case II, \( k \) does not include \( \cos^2 \alpha \)). Employing Equation (11), Equation (15) can be rewritten as

$$r = 1 + \frac{k \Omega^{-a} B_{c12}^{-b}}{B_{c12}^{-b}},$$

(16)

where \( B_{c12} \) is the characteristic magnetic field in units of \( 10^{12} \) G. When \( 2 - b > 0 \), and considering the polar magnetic field is always larger than or equal to the characteristic magnetic field, there is a lower limit on the spindown ratio in each acceleration model

$$r \geq 1 + k \Omega^{-a} B_{c12}^{-b}.$$  

(17)

Observationally, PSR B1931+24 has the smallest spindown ratio: \( r = 1.5 \) (Kramer et al. 2006). Acceleration potentials with minimum spindown ratios larger than 1.5 can be ruled out. At the same time, if the corresponding magnetic inclination angle is very small and the polar magnetic field is too large, then the acceleration potential is also not favored. Only two models meet these two criteria: SCLF (II, CR) and the CAP model. The magnetic inclination angle in case II is similar to the corresponding values in case I (at most a few degrees larger).

Table 3

| Pulsar Name | VG(CR) | VG(ICS) | SCLF(II, CR) | SCLF(II, ICS) | SCLF(I) | OG | CAP |
|-------------|--------|---------|--------------|--------------|--------|----|-----|
| B1931+24    | 2.3    | 2.4     | 2.4          | -            | 2.3    | 1.7| 2.3 |
| J1841−0500  | 1.7    | 1.9     | 2.0          | -            | 1.7    | 0.77| 1.8 |
| J1832+0029  | 2.1    | 2.2     | 2.2          | -            | 2.1    | 1.4| 2.1 |
| \( n_{\text{min}} \) | 0.86  | 1.1     | 1.3          | 2.4          | 0.86   | -0.71| 1 |

Notes. The last row shows the minimum braking index for each model.

\( ^{a} \) SCLF (II, ICS) can already be ruled out.

The Astrophysical Journal, 788:16 (6pp), 2014 June 10

Li et al.
3.4. Duty Cycle of Particle Wind Determined from Timing Observations

The particle wind component may only work for part of the time (Harding et al. 1999; Tong et al. 2013). Denoting the duty cycle of particle wind as $D_p$ (fractional time when the particle wind is present), the long term averaged spindown of the pulsar is (Harding et al. 1999)

$$-I\dot{\Omega}_{\text{ave}} = \dot{E}_d(1-D_p) + \dot{E}D_p,$$

where $\dot{\Omega}_{\text{ave}}$ is the long-term averaged spindown rate. For intermittent pulsars, from Equations (7) and (8), Equation (18) can be rewritten as

$$\dot{\Omega}_{\text{ave}} = \dot{\Omega}_{\text{off}}(1-D_p) + \dot{\Omega}_{\text{on}}D_p.$$  

Therefore, the duty cycle of particle wind can be determined from timing observations

$$D_p = \frac{\dot{\Omega}_{\text{ave}} - \dot{\Omega}_{\text{off}}}{\dot{\Omega}_{\text{on}} - \dot{\Omega}_{\text{off}}} = \frac{\dot{v}_{\text{ave}} - \dot{v}_{\text{off}}}{\dot{v}_{\text{on}} - \dot{v}_{\text{off}}}.$$  

At present, only PSR B1931+24 had $\dot{v}_{\text{on}}, \dot{v}_{\text{off}}$ and $\dot{v}_{\text{ave}}$ reported (Kramer et al. 2006). From the long-term averaged spindown, the duty cycle of its particle wind is $D_p = 26\%$. In the pulsar wind model, the presence of particle wind corresponds to the on state. Then the duty cycle of particle wind should be the same as the duty cycle of the on state. Kramer et al. (2006) estimated that the duty cycle of the on state is $\sim 20\%$. A later study gave a duty cycle of the on state as $26\% \pm 6\%$ (Young et al. 2013). The two duty cycles, the one obtained from long term averaged spindown (Equation (20)) and that from radiation monitoring, are consistent with each other. We suggest that future timing observations of intermittent pulsars not only give the spindown rates during the on/off states ($\dot{v}_{\text{on}}$ and $\dot{v}_{\text{off}}$), but also the long-term averaged spindown rate ($\dot{v}_{\text{ave}}$).

4. DISCUSSIONS AND CONCLUSIONS

In pulsar works, the magnetic dipole braking assumption is often employed, e.g., in calculating the characteristic magnetic field and the characteristic age. The magnetic dipole braking assumes a rotating perpendicular dipole in vacuum. A real pulsar must have a magnetosphere (Goldreich & Julian 1969). Pulsars can radiate radio and high-energy photons. Therefore, in the pulsar magnetosphere there must be some kind of particle acceleration and radiation. Previous studies showed that the magnetic dipole braking assumption is correct to the lowest order approximation (Goldreich & Julian 1969; Xu & Qiao 2001; Contopoulos & Spitzer 2006). When considering higher order effects, e.g., braking index, timing noise, and intermittent pulsars, physically based models must be employed. Therefore, the magnetic dipole braking model is just a pedagogical model (Shapiro & Teukolsky 1983). The characteristic magnetic field is just the effective magnetic field (all the torque terms are attributed to a perpendicular dipole field).

Applying the pulsar wind model of Xu & Qiao (2001) to the three intermittent pulsars, we calculated their corresponding inclination angles and braking indices. Tables 2 and 3 show that the results are quite different from each other because they have different acceleration potentials. In modeling the particle wind component, only one kind of acceleration potential is considered. The real case may allow the coexistence of different acceleration potentials (e.g., a core gap and a more extended one, Qiao et al. 2007; Du et al. 2010). When intermittent pulsars have more observations, it will be necessary to check the coexistence of different acceleration potentials. Considering the seven acceleration potentials in Tables 2 and 3 (one of them can already be ruled out), we suggest that the curvature-induced VG model (VG (CR) model; Ruderman & Sutherland 1975) be compared with observations first.10

From the above calculations, the ICS-induced space charge limited flow with field saturation (i.e., the SCLF (II, ICS) model) can already be ruled out. The corresponding magnetic inclination angle is too small and the polar magnetic field is in the magnetar range. On the other hand, this may actually happen in some magnetars. Magnetars may be wind braking and some of them may have a small inclination angle and a very high dipole magnetic field (Tong & Xu 2012; Tong et al. 2013). For PSR J1841–0500, its inclination angle is also relatively small in the CAP case. This depends on the gap potential adopted ($3 \times 10^{12} V$ at present). If the gap potential is $10^{13} V$, then the consequent inclination angle will be $18$ deg.

The spindown behavior of intermittent pulsars looks like a glitch in the interval between successive on states (e.g., Figure 1 in Camilo et al. 2012). However, a more physically motivated explanation is that the absence of particle outflow is responsible for both the cessation of radio emission and the lower slow down rate during the off state (Kramer et al. 2006; and this paper). The opposite case is also possible: the particle outflow may be significantly stronger. Then the spindown behavior of the pulsar will look like a negative glitch. Such negative glitch has already been observed in one magnetar (i.e., anti-glitch; Archibald et al. 2013). A stronger particle wind during the observational interval can explain the anti-glitch (Tong 2014). Therefore, the spindown behavior of intermittent pulsars can be understood uniformly in the wind braking scenario.

The effective model proposed by Kramer et al. (2006) explains the different spindown ratio of intermittent pulsars by a different particle density. PSR J1841–0500 has the largest spindown ratio ($r = 2.5$). Adopting the prescription of Kramer et al. (2006), the required plasma density is three times the Goldreich–Julian density (Lorimer et al. 2012). In our model, the charge density in the acceleration region (i.e., primary particles) can always be the Goldreich–Julian density. A constant amount of charged particles accelerated may ensure that different on states of intermittent pulsars are stable (Young et al. 2013). Kramer et al. (2006) employed the pulsar wind model of Harding et al. (1999) to treat the wind torque. It is equivalent to the case in which the accelerated particles can attain the maximum potential (Tong et al. 2013). In the real case, the acceleration gap must break down somewhere due to pair screening (Ruderman & Sutherland 1975). Kramer et al. (2006) also assumed an orthogonal rotator when calculating the surface dipole field using the off state spindown rate. In our pulsar wind model, physically motivated particle acceleration potentials are taken into consideration. For a specific particle acceleration potential, the spindown ratio is determined by the magnetic inclination angle (see Figure 1). The surface dipole field and the magnetic inclination angle are solved simultaneously.

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10 Since it was among the first pulsar models proposed and is still user-friendly. However, for normal pulsars with non-magnetar strength field, space charge limited flow models are favored, unless the central star is a bare quark star (Yu & Xu 2011, and references therein).
In the pulsar wind model considered in this paper, there is a particle wind torque in addition to the magnetic dipole torque during the on state. Therefore, the spindown rate should always be larger in the on state than in the off state. Previous works also discussed the possibility of no dipole radiation during the on state (e.g., Gurevich & Istomin 2007). From Equation (12), if there is no dipole term in the on state, the spindown ratio will be proportional to \( \cot^2 \alpha \) (see also Gurevich & Istomin 2007; Beskin & Nokhrina 2007). For large inclination angle, the spindown ratio can be smaller than one. Some intermittent pulsars are expected to have smaller spindown rates in the on state than in the off state. However, the present three sources all have larger spindown rates during the on state. Therefore, it is more likely that the dipole term coexists with the particle wind term in the on state of intermittent pulsars (and normal pulsars).

Li et al. (2012b) modeled the spindown of intermittent pulsars using different states of pulsar magnetosphere. Their work is from the point of view of the magnetohydrodynamical simulation. The current of charged particles is modeled by introducing some dissipation in the magnetosphere. The Li et al. (2012b) model can be viewed as a macroscopic version of particle wind, while this work treats the particle wind from the microscopic point of view. The spindown ratio also depends on the magnetic inclination angle in Li et al. (2012b). Li et al. (2012b) and this work predict quantitatively different inclination angles (see their Figure 4 and Figure 1 in this paper). Our pulsar wind model can predict the braking index of the intermittent pulsar (with braking index between one and three).

Since intermittent pulsars are very weak, therefore large telescopes (e.g., Arecibo and the Five hundred meter Aperture Spherical radio Telescope, known as FAST) are required to make polarization observations. In the future, the FAST pulsar survey may discover more intermittent pulsars (Nan et al. 2011). Polarization observations of more intermittent pulsars will help us test different models of pulsar magnetospheres. In combination with the Green Bank Telescope (and other large telescopes), the braking index of intermittent pulsars (the present three sources and more to be discovered) may be measured. For one intermittent pulsar, if the spindown ratio, the magnetic inclination angle, and the braking index are all measured, they will provide very strong constraint on our understanding of pulsar magnetospheres.

In summary, the pulsar wind model of Xu & Qiao (2001) is employed to explain the spindown behavior of intermittent pulsars. The enhanced spindown during the on state is due to the presence of an additional particle wind. In modeling the pulsar wind, the effect of particle acceleration is included. Using the measured spindown ratio, the magnetic field and the inclination angle of intermittent pulsars are solved simultaneously. Their predicted braking indices are also shown. The density of the accelerated particles can always equal the Goldreich–Julian density. This may guarantee that different on states of intermittent pulsars are very stable. The duty cycle of particle wind can be determined from the long-term averaged spindown. It is consistent with the cycle of the on state.

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