Spindown of pulsars interacting with companion winds: implications for the double pulsar PSR J0737-3039

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Abstract

The spindown of isolated pulsars, both aligned and oblique, has been extensively studied over the past few decades. However, in binary systems, the interaction with the companion wind can significantly alter the spindown of the pulsar. In this study, we use the particle-in-cell method to measure the spindown of pulsars surrounded by relativistic winds from companion stars, where the stand-off distance between the magnetosphere and the shocked wind is well inside the light cylinder of the pulsar. Our results show that the spindown of the aligned component is enhanced due to the confinement of the magnetosphere by the wind, while the oblique component is suppressed due to the mismatch between the pulsar wind stripe wavelength and the waveguide formed by the cavity in the companion wind. This difference from the well-known spindown formula affects the estimate of the surface magnetic field strength in observed pulsar systems. We apply our findings to the double pulsar system PSR J0737–3039, where a normal 2-second pulsar PSR J0737–3039B is thought to be surrounded by a wind produced by its millisecond companion PSR J0737–3039A, with a shock stand-off distance estimated to be 1/3 of its light cylinder. We provide updated estimates of magnetic field strength of PSR J0737–3039B, and discuss the particle acceleration in its unusual magnetosphere with implications for its high energy emissions.

Motivation: double pulsar system PSR J0737-3039

The first double pulsar system PSR J0737-3039 consists of a millisecond pulsar PSR J0737-3039A ($P \sim 2$ ms) and a normal pulsar PSR J0737-3039B ($P \sim 2$ s) (Burgay et al. 2003). This system has the following unusual properties:

1. **A highly relativistic and weakly magnetized pulsar wind from PSR J0737-3039A**, with wind lorentz factor $\gamma \gtrsim 10$. It interacts with the magnetosphere of PSR J0737-3039B, which produces a bow shock and a magnetopause that is defined by the standoff distance $R_{\rm m}$;
2. **The magnetopause that resides well inside the light cylinder of PSR J0737-3039B** ($R_{\rm L} \equiv c/\Omega$, where Ω is the stellar rotation angular frequency), or more specifically, $R_{\rm m}/R_{\rm L} \sim 1/3$. This implies that the energy loss rate $L_{\rm iso}$ from PSR J0737-3039B through electromagnetic torques can be significantly altered by the interaction with its companion wind, and thus deviates from the well-known analytical formula being used to estimate the magnetic field strength of isolated pulsars (Spitkovsky 2006)

$$L_{\rm iso} \sim \frac{\mu^2 \Omega^4}{c}(1+\sin^2\chi). \tag{1}$$

Here μ and χ stand for the magnetic moment, and the misalignment angle between rotation and magnetic axes of pulsar, and c is the speed of light.

What we are trying to elucidate in this study is how does the interaction of pulsar magnetosphere with its companion wind change its energy loss and thus spindown rate, as well as the particle acceleration happening inside this anomalous magnetosphere.

Numerical setup

We use particle-in-cell (PIC) code `TRISTAN-MP` to simulate the interaction between a pulsar magnetosphere and its companion wind. For the pulsar magnetosphere, we create a rotating dipolar magnetic field with magnetic moment μ by phasing currents through three orthogonal current rings located at the center of the star. The normals of the rings are aligned with coordinate axes. Taking the neutron star as a perfect conductor, we set the corotating electric field inside the star as $\mathbf{E_{cor}} = -(\mathbf{\Omega} \times \mathbf{r})/c \times \mathbf{B} \quad (|\mathbf{r}| \le R_*)$, where $\mathbf{r}$ and $\mathbf{B}$ are the radial position and its corresponding magnetic field. We first leave this vacuum rotator evolving for around 1 light cossing time from the stellar surface to the outer boundary. We inject neutral plasma around NS surface to mimic the pair production in the magnetosphere, and damp the perpendicular momentum of particles trapped in the closed zone with respect to the local magnetic field in the $E \times B$ frame to mimic the synchrotron cooling. To model the effect of wind magnetopause, we put a perfect conductor with semi-parabolic shape (Shue et al. 1997)

$$\xi_{\rm m} = R_{\rm m}\left(\frac{2}{1+\cos\psi}\right)^{\alpha}, \tag{2}$$

where the parameter $\alpha = 0.6$ is used to match the shape of wind-magnetosphere simulations. A representative snapshot of our simulation is shown in Fig. 1.

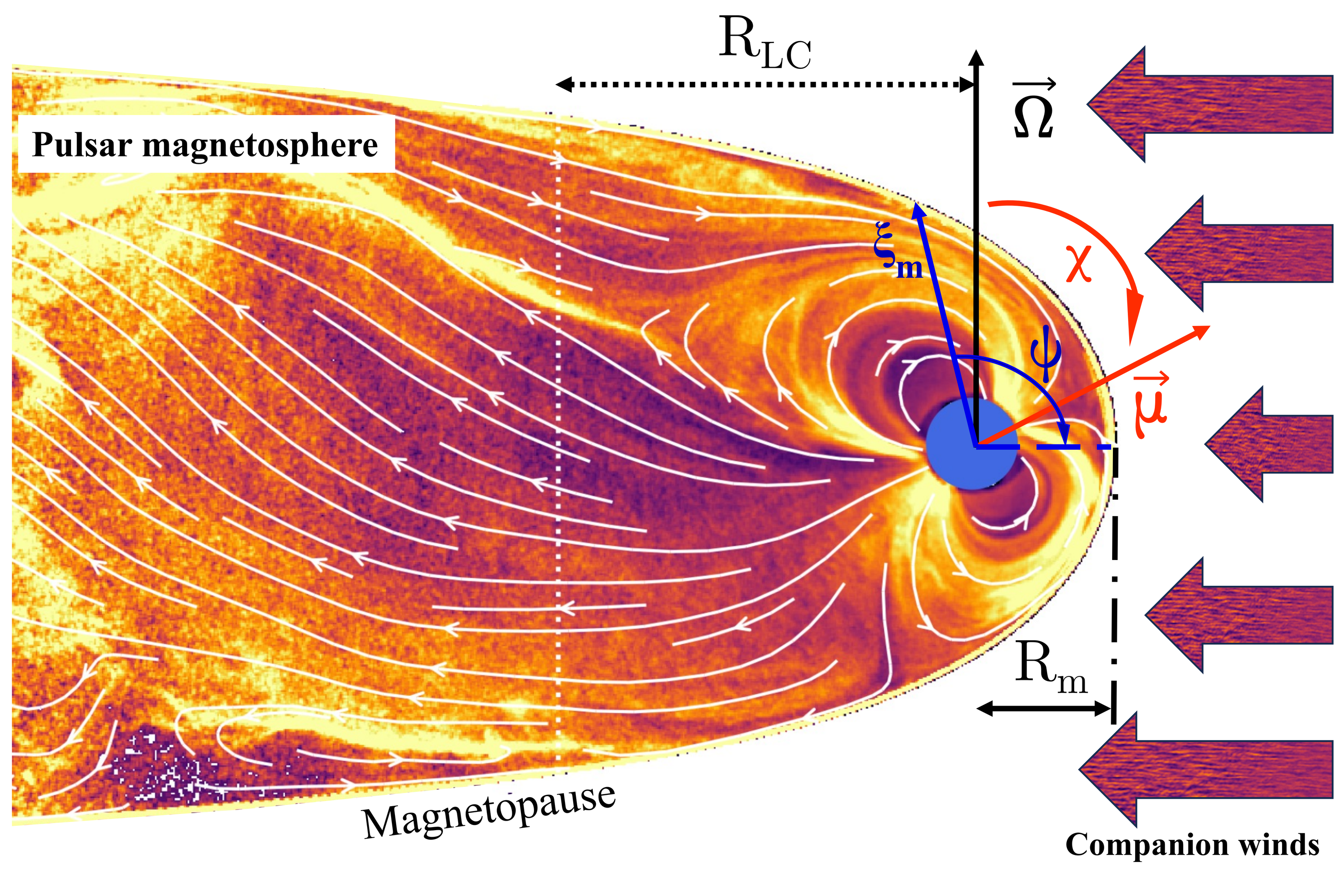

Figure 1. An oblique rotator magnetosphere ($\chi = 60°$) confined by companion wind with $R_{\rm m}/R_{\rm L} = 1/3$; color shows pulsar plasma density.

We explore the parameter regime where $R_{\rm m}/R_{\rm L} \lesssim 1$ for both aligned and perpendicular rotators. We measure the Poynting flux through concentric spheres

$$L_r \equiv \frac{c}{4\pi}\oiint_r (\mathbf{E}\times\mathbf{B})\cdot \mathbf{dS} \tag{3}$$

and compare it to the spindown value without the enclosure, $L_{\rm iso}$, to evaluate the effects of companion winds with respect to the confinement parameter $R_{\rm m}/R_{\rm LC}$.

Results

Aligned rotator ($\chi = 0$)

The radial dependence of Poynting flux $L_r/L_{\rm iso}$ for cases with different $R_{\rm m}/R_{\rm L}$ is shown in Fig. 2; we can see that the spindown is **enhanced** with $R_{\rm m}/R_L \lesssim 1$. This is mainly due to the increased open flux from the inwardly moving Y-point (e.g., see the right panel of Fig. 2 for the zoom-in density map and field lines around the light cylinder for the case with $R_{\rm m}/R_{\rm L} = 1/3$). Meanwhile, the dissipation also gets stronger when $R_{\rm m}/R_{\rm L}$ decreases (see the L_r-r curve beyond $R_{\rm m}$ in left panel of Fig. 2), due to the stronger reconnection both in current sheets and the equatorial plane around wind enclosures (poloidal map of dissipation rate in the left panel of Fig. 2). PSR J0737-3039B, whose $R_{\rm m}/R_{\rm L} \sim 1/3$, is expected to spindown with $\sim 3L_{\rm iso}$ (see the plateau value $L_{r,{\rm pla}}$ highlighted with the black dashed line in the left panel of Fig. 2), while losing $\sim 2/3$ of this energy into high energy emission through reconnection. The spindown rate $L_{r,{\rm pla}}$ is found to scale with $(R_{\rm m}/R_{\rm L})^{-0.42}$, which gives the braking index $n \equiv -\Omega\ddot{\Omega}/\dot{\Omega}^2 \sim 2.58$, assuming $R_{\rm m}$ to be constant.

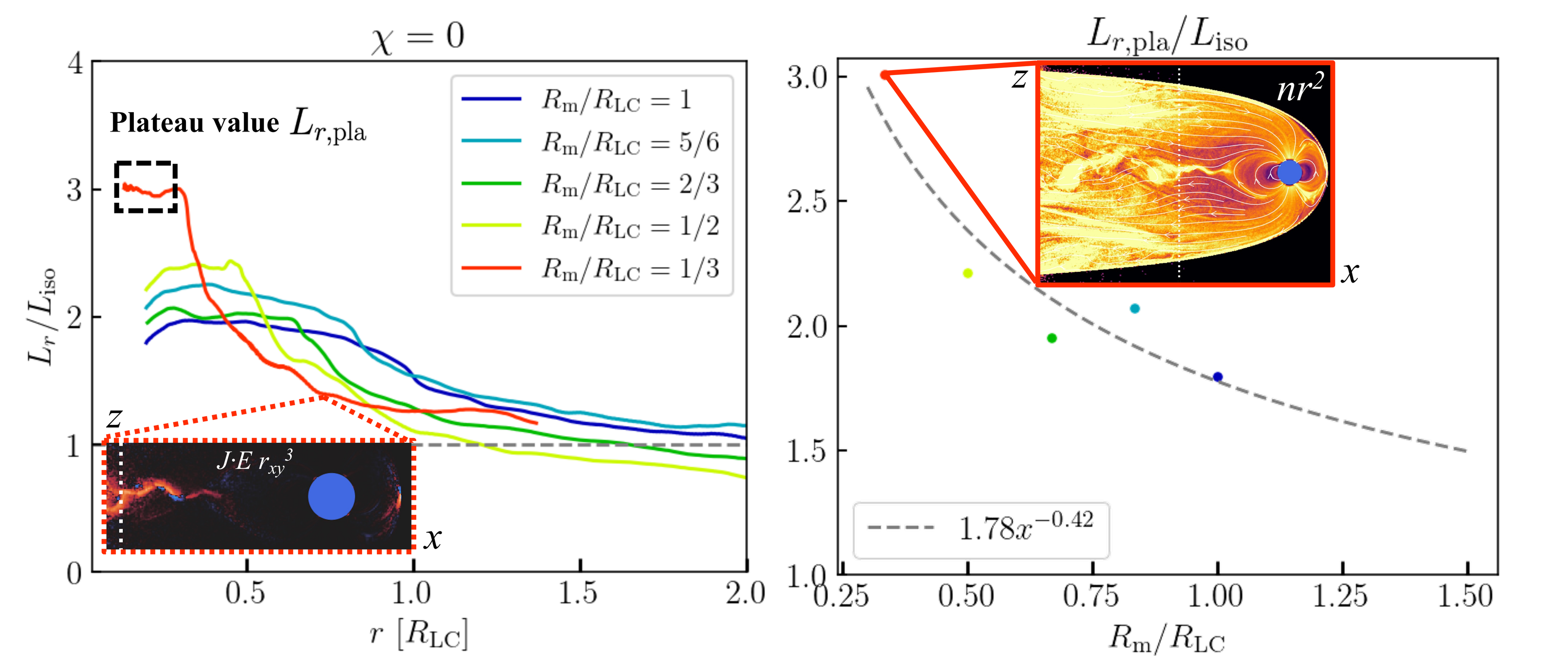

Figure 2. Poynting flux from confined magnetospheres with $R_{\rm m}/R_{\rm L} = 1/3, 1/2, 2/3, 5/6, 1$: radial dependence with the zoom-in poloidal map of $J \cdot E$ (left panel), the plateau value of each case together with the magnetospheric structure for $R_{\rm m}/R_{\rm L} \sim 1/3$ (right panel; white dotted lines stand for light cylinder). The grey dashed line shows the fitting formula.

Oblique rotator ($\chi \neq 0$)

The radial dependence of time-averaged Poynting flux $\bar{L}_r/L_{\rm iso}$ for cases with $R_{\rm m}/R_{\rm LC} = 1/2, 1/3$ and $\chi = 0°, 60°$ and $90°$ are shown as solid lines in the left panel of Fig. 3. We show the time variability for the case with $R_{\rm m}/R_{\rm LC} = 1/3, \chi = 90°$ in the right panel as the thin sequence around the time-averaged curve (thick red line), comparing to the vacuum solution (dotted red line). We found that the Poynting flux is killed with the wind enclosure $R_{\rm m}/R_{\rm LC} \lesssim 1$ in vacuum, due to the waveguide cutoff effect. Nevertheless, with the same $R_{\rm m}/R_{\rm LC}$, the time-averaged Poynting flux is **suppressed** but is not zero for plasma-filled magnetospheres. Comparing the L_r map in the equatorial plane between vacuum rotators and plasma-filled rotators, we can see extra energy carried by the outflowing plasma for plasma-filled rotators (see the L_r map in the right panel of Fig. 3), which is not killed by the waveguide effects.

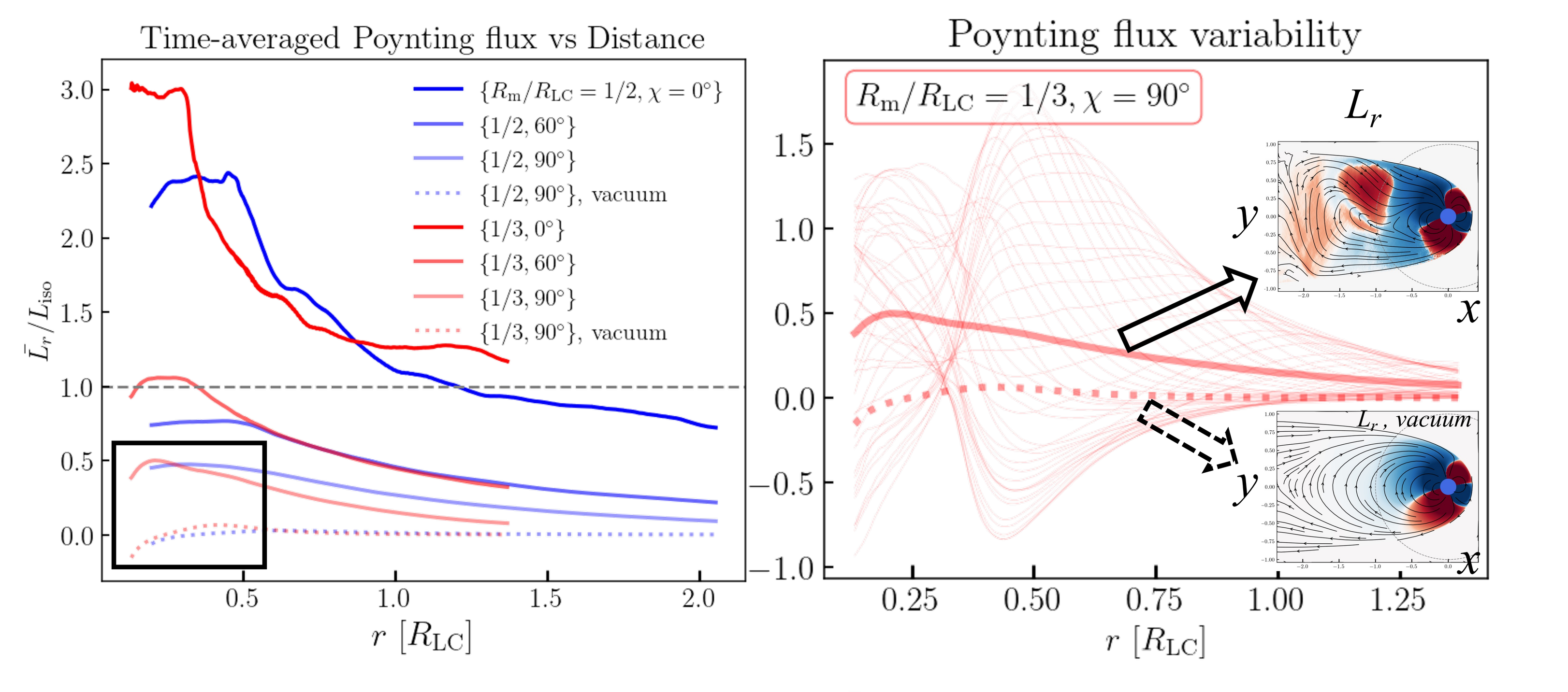

Figure 3. The radial dependence of time-averaged Poynting flux $\bar{L}_r$ from confined magnetosphere with $R_{\rm m}/R_{\rm L} = 1/3$ and 1/2 for aligned and oblique rotators (left panel). In the right panel, thin red sequence shows the time evolution of $R_{\rm m}/R_{\rm LC} = 1/3, \chi = 90°$, while the thick solid and dotted line mark the time-averaged behavior with plasma and in vacuum. For comparison, we show the field configuration in L_r maps in the equatorial plane as insets in right panel.

Conclusions and discussions

We studied the spindown of pulsars confined by companion winds, with the wind standoff distance inside their light cylinder. We found that the spindown to be enhanced for aligned rotators, while being suppressed for perpendicular rotators; the dissipation in both cases is stronger than for corresponding isolated rotators due to the enhanced current sheet reconnection, which is a potential source for particle acceleration and nonthermal radiation. Modifications to spindown power due to wind compression should be included in the determination of magnetic field strength of PSR J0737-3039B.

Bibliography

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