So, How Do Radio Pulsars Slow-Down?

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In 1983 our team has shown that for zero longitudinal electric current circulating in the pulsar magnetosphere, the energy losses $W_{\rm tot}$ vanish for any inclination angle χ [1]. This effect (confirmed later by L.Mestel group [2]) results from full screening of the magneto-dipole radiation by the magnetospheric plasma. This implies that the pulsar braking results solely from the impact of the torque $\mathbf{K}$ due to the longitudinal currents.

On the other hand, rotating magnetized star can be slowed down only due to action of the Ampére force associated with surface currents $\mathbf{J}_{\rm s}$: $W_{\rm tot} = -\mathbf{\Omega}\mathbf{K}$, where

$$\mathbf{K} = \frac{R^3}{c}\int \mathbf{J}_{\rm s}\,(\mathbf{B}\mathbf{n})\,{\rm d}o = \frac{R^3}{4\pi}\int \{[\mathbf{n}\times\mathbf{B}^{(3)}](\mathbf{B}^{(0)}\mathbf{n}) + [\mathbf{n}\times\mathbf{B}^{(0)}](\mathbf{B}^{(3)}\mathbf{n})\}\,{\rm d}o. \qquad (1)$$

Here indices $(0,3)$ correspond to expansion powers in terms of the small parameter $\varepsilon = \Omega R/c$. Careful analysis for the vacuum magneto-dipole radiation shows surprisingly that in the Landau-Lifshitz solution both terms play a role, while in the Deutsch solution only the first one does (giving, certainly, the same well-known result).

Returning to the magnetosphere filled with plasma, one can find that the torque acting on the star via the surface currents $\mathbf{J}_{\rm s}$ closing the longitudinal electric currents [1]

$$K_{\parallel}^{\rm sur} \approx -\frac{\mathbf{m}^2\Omega^3}{c^3} i_{\rm s}, \quad K_{\perp}^{\rm sur} \approx -\frac{\mathbf{m}^2\Omega^3}{c^3}\left(\frac{\Omega R}{c}\right) i_{\rm a}, \quad I_{\rm r}\,\dot{\Omega} = K_{\parallel}^{\rm A} + (K_{\perp}^{\rm A} - K_{\parallel}^{\rm A})\sin^2\chi, \quad (2)$$

corresponds to the first term in (1). Here we have introduced two components of the torque $\mathbf{K}$, parallel and perpendicular to the magnetic dipole $\mathbf{m}$. Besides, the dimensionless current $i = j_{\parallel}/j_{\rm GJ}$ (normalized to the 'local' Goldreich-Julian current density $j_{\rm GJ} = |\mathbf{\Omega}\cdot\mathbf{B}|/2\pi$ with the scalar product) is also separated into symmetric and antisymmetric contributions, $i_{\rm s}$ and $i_{\rm a}$, depending on whether the direction of the current in the north and south parts of the polar cap is the same or opposite.

Hence, to satisfy the Spitkovsky's relation $\dot{\Omega} \propto (1 + \sin^2\chi)$ we have to assume too large antisymmetric current $i_{\rm a} \sim \varepsilon^{-1}$ while in reality $i_{\rm a} \sim \varepsilon^{-1/2}$. Thus, it is necessary to introduce an additional contribution resulting from the mismatch between the magneto-dipole and magnetospheric radiation and corresponding to the second term in (1)

$$K_{\perp}^{\rm mag} = -A\,\frac{B_0^2\Omega^3R^6}{c^3}\,i_{\rm a}. \qquad (3)$$

For $i_{\rm a} \sim \varepsilon^{-1/2}$ we obtain $A \sim \varepsilon^{1/2}$. This implies that for local GJ current $i_{\rm a} \approx 1$, for most inclination angles, one can neglect the additional term $K_{\perp}^{\rm mag}$, as was done in [1].

References

[1] V. S. Beskin, A. V. Gurevich & Ya. N. Istomin, 1983, Sov. Phys. JETP 58, 235

[2] Mestel, L., Panagi, P., & Shibata, S. 1999, MNRAS, 309, 388