# So How Do Radio Pulsars Slow-Down?

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

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

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

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

Returning to magnetosphere filling with plasma, one can find that the torque acting on the star by 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 first term in (1). Here we introduce two components of the torque **K** parallel and perpendicular to the magnetic dipole **m**. Besides, dimensionless current $i = j_{\parallel}/j_{\rm GJ}$ (normalization to 'local' Goldreich-Julian current density $j_{\rm GJ} = |\mathbf{\Omega}\cdot\mathbf{B}|/2\pi$ with scalar product) also separated into symmetric and antisymmetric contributions, $i_{\rm s}$ and $i_{\rm a}$, depending upon whether the direction of the current is the same in the north and south parts of the polar cap, or opposite.

Hence, to satisfy Spitkovsky's relation $\dot{\Omega} \propto (1+\sin^2\chi)$ we should 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 assume additional contribution resulting from mismatch between magneto-dipole and magnetospheric radiation and corresponding to the second term in (1)

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

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, *Sov. Phys. JETP* 58, 235 (1983)

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