Centrifugal acceleration of bulk motion of plasma by rotation powered pulsars

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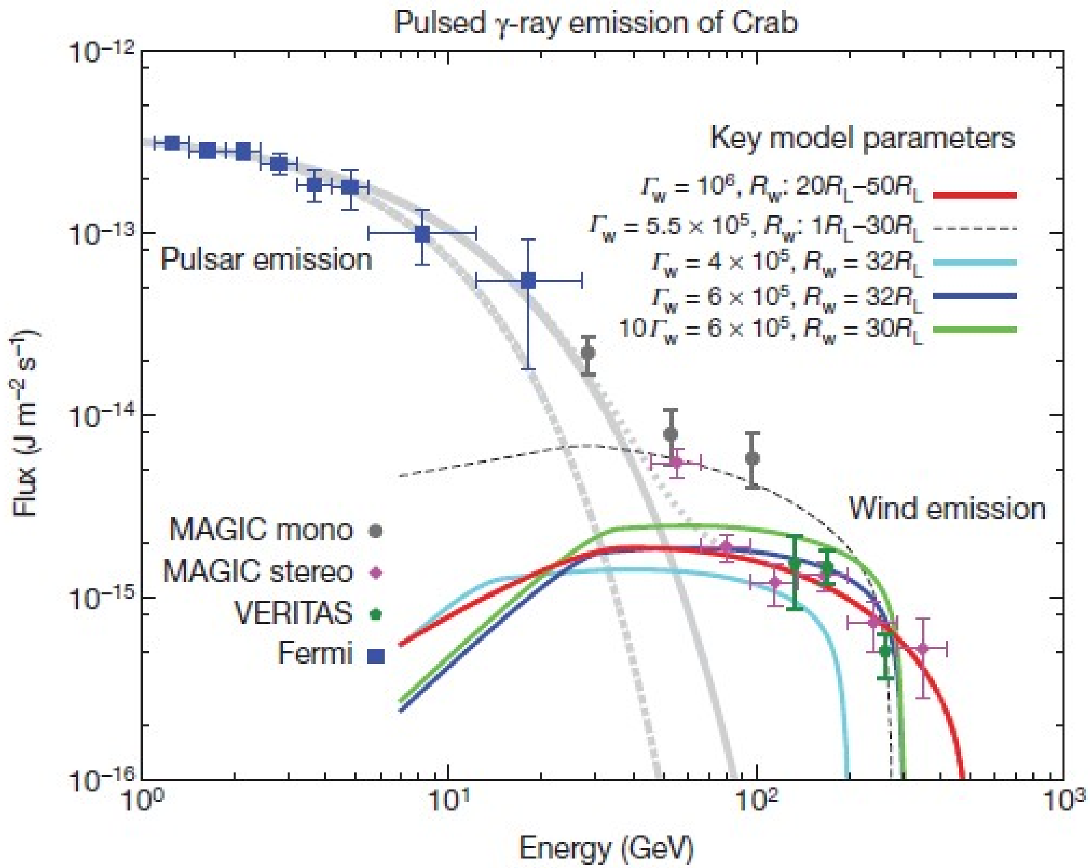
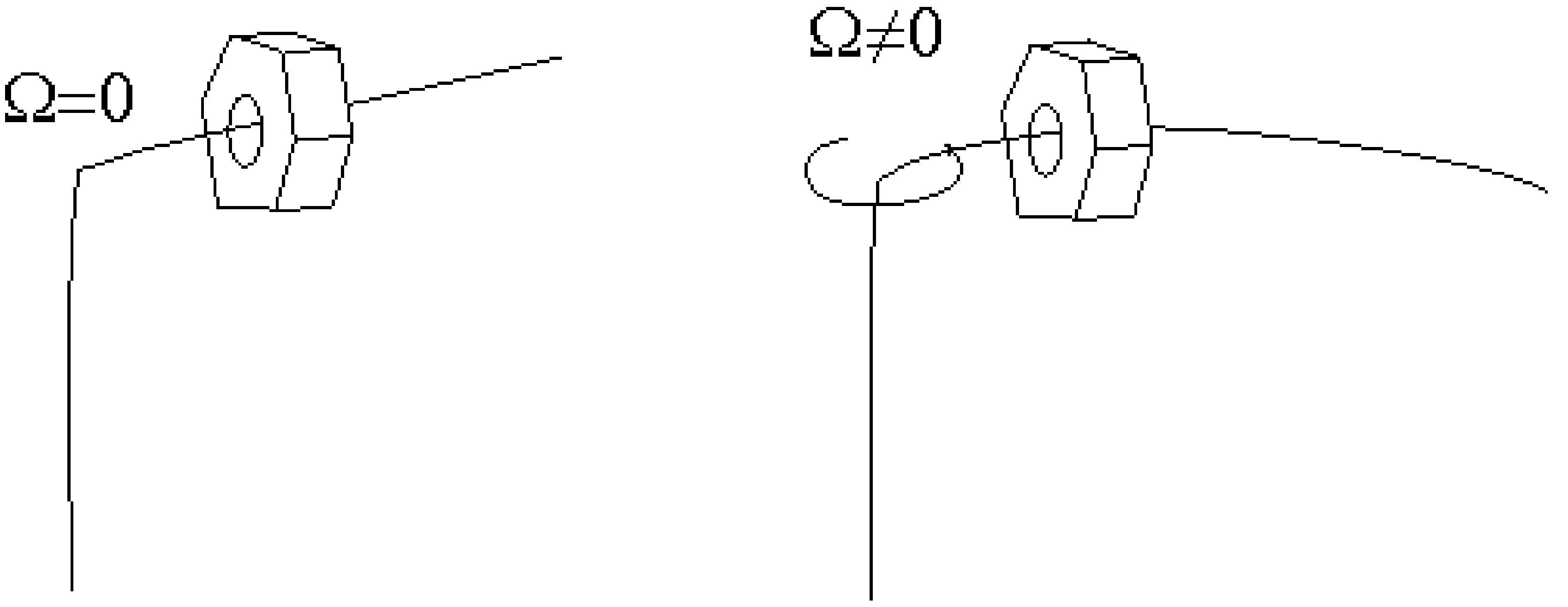
Observation of pulsed VHE gamma – rays up to 400 GeV from Crab pulsar

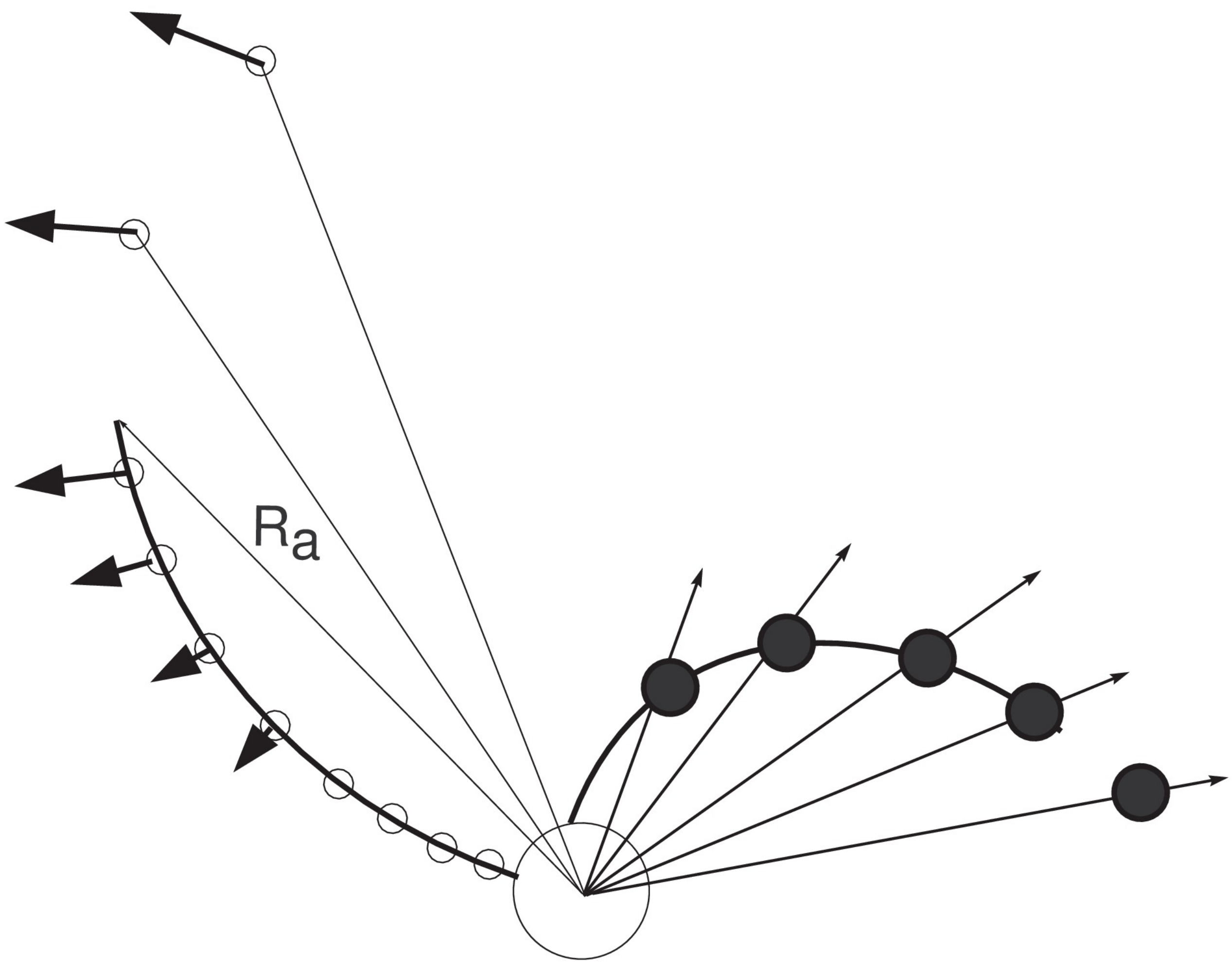


Electrostatic gap models do not provide generation of such a radiation

Mechanism of the centrufugal acceleration



Mechanical consideration



Centrifugal acceleration along a straight wire

$$m\frac{dU}{dt}=m\,\gamma\frac{v_\varphi^2}{r}$$

F.Rieger (2011)

$$v_\varphi=\Omega r$$

$$\gamma\sim\left(1-\left(\Omega r/c\right)^2\right)^{-1}$$

$$v_r\sim\sqrt{1-\left(\Omega r/c\right)^2}$$

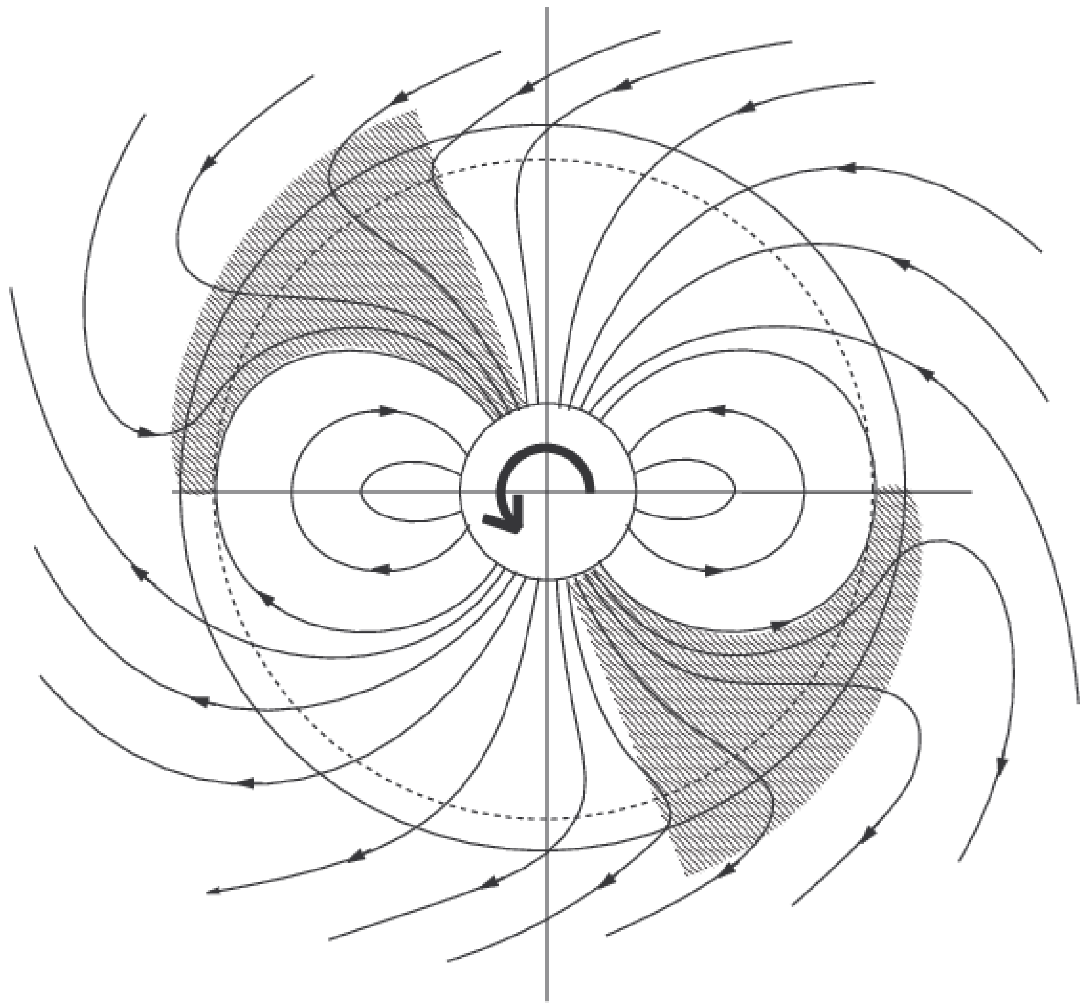
Why the magnetocentrifugal acceleration does not work in the axisymmetric case ?

1. The twist of the field lines is defined by the inertia of plasma

2. The inertia of the plasma consists of the inertia of the matter and inertia of the magnetic field.

- The inertia of the magnetic field twists the field lines into perfect Archimedian spiral provided that initially (without rotation) the magnetif field is axisymmetric. The result — No acceleration

Why we can expect an efficient acceleration in real pulsar



Objectives of the present work

To consider the process of acceleration in prescribed 3-D magnetic field.

- How the bulk motion of plasma is accelerated if some field lines differs from Archimedian spiral?
- How strong should be the difference to provide the effcient acceleration?
- What is the energy of the plasma?

Acceleration of plasma in the rotating magnetic field

$$\rho\Omega c\dot{\mathbf{U}} = q\mathbf{E} + \frac{1}{c}[\mathbf{j}\times\mathbf{B}]$$

$$\dot{\mathbf{U}} = \frac{\partial \mathbf{U}}{\Omega\partial t} + v_k\frac{\partial \mathbf{U}}{\partial x_k}.$$

$$\mathbf{E} + [\mathbf{v}\times\mathbf{B}] = 0.$$

$$\mathbf{E} = -[\mathbf{V}_{\mathbf{rot}}\times\mathbf{B}],$$

$$\text{where } \mathbf{V}_{rot} = [\mathbf{e}_z\times\mathbf{r}].$$

$$\mathbf{U}_B\cdot\dot{\mathbf{U}} = 0, \quad \text{where } \mathbf{U}_B = \gamma\mathbf{v}_B.$$

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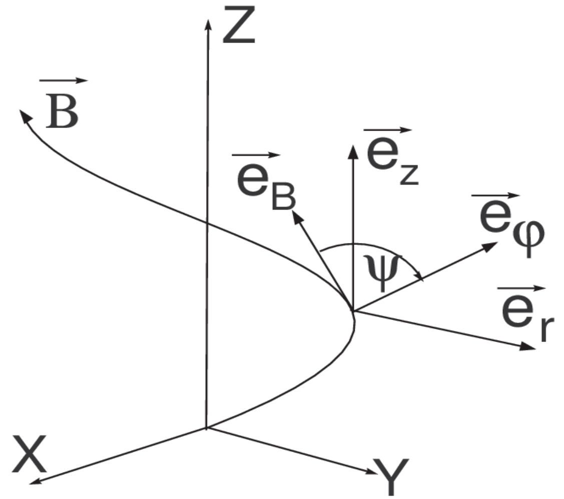
Solution of the problem

$$(1-v_d^2)v_r\frac{\partial\gamma}{\partial r}=\gamma(rv_r\sin^2\psi+v_Bv_\varphi(\mathbf{e}_r\mathbf{e}_B)\cdot\ +\frac{rv_r\dot{\cos}\,\psi}{(\mathbf{e}_r\mathbf{e}_B)});$$

where

$$\dot{\cos}\,\psi=v_r\frac{\partial\cos\psi}{\partial r}. \qquad \cos\psi=\mathbf{e}_\varphi\cdot\mathbf{e}_\mathrm{B} \qquad \mathbf{v}_\mathrm{d}=[\mathbf{E}\times\mathbf{B}]/\mathbf{B}^2.$$



Parametrisation of the field line by the archimedian spiral

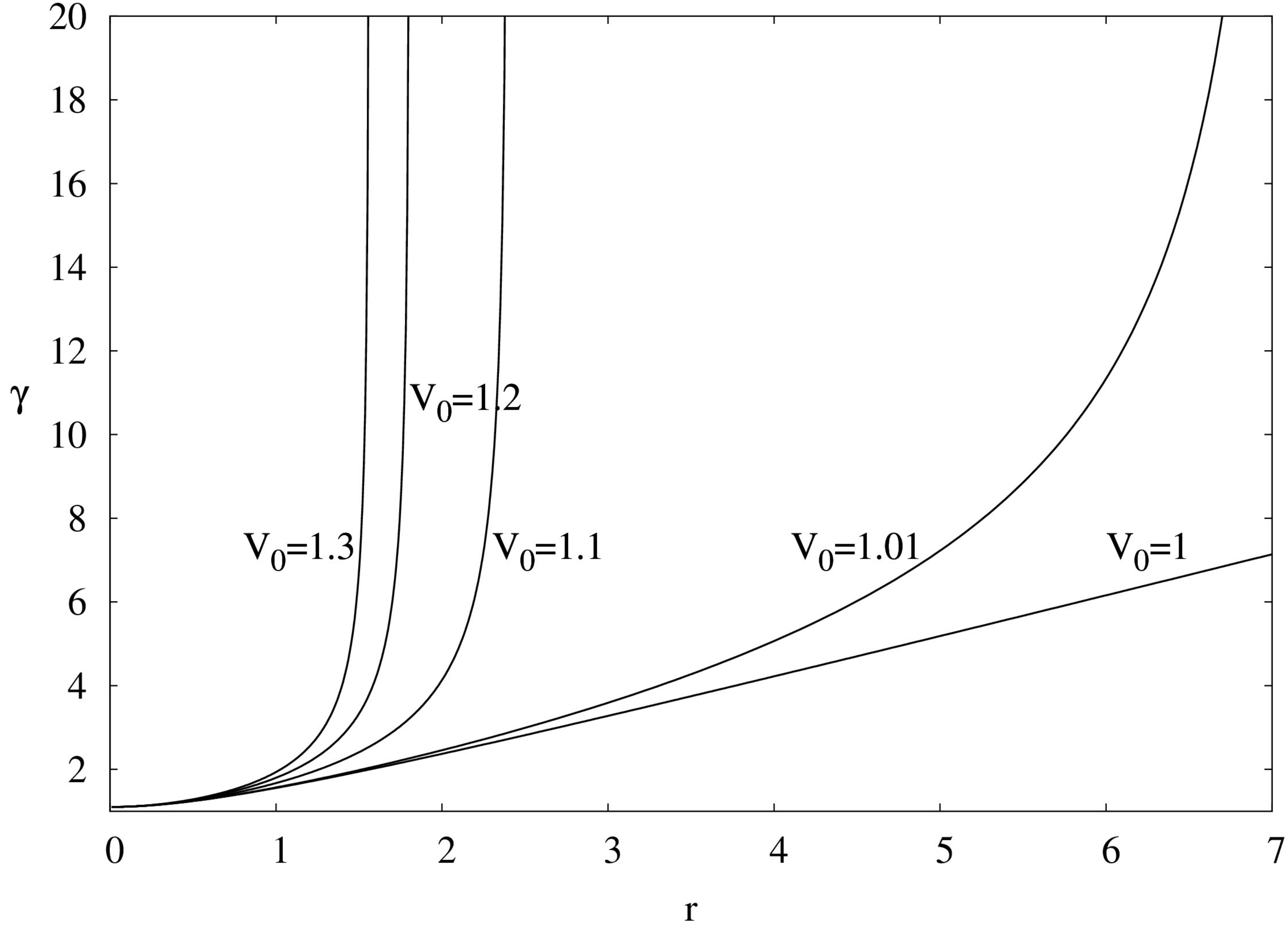
$$\Phi = -\frac{r}{\sin\alpha V_0},$$

Vo is a parameter,

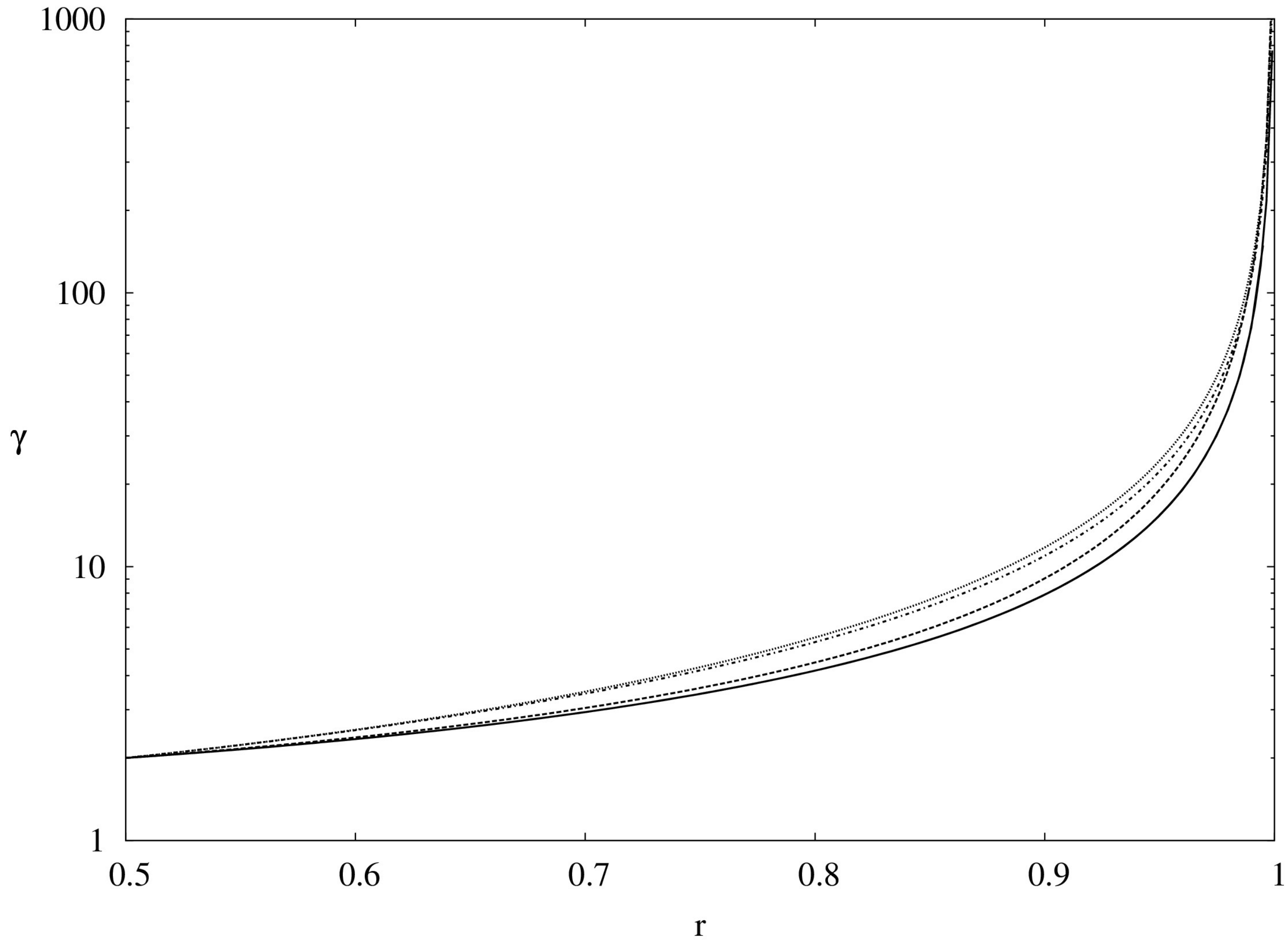
Vo < 1 - real case

Vo > 1 — Archimedian spiral with the twist less than in the case Vo=1.

Solution at Vo > 1 (negative twist)



Acceleration at positive twist Vo < 0

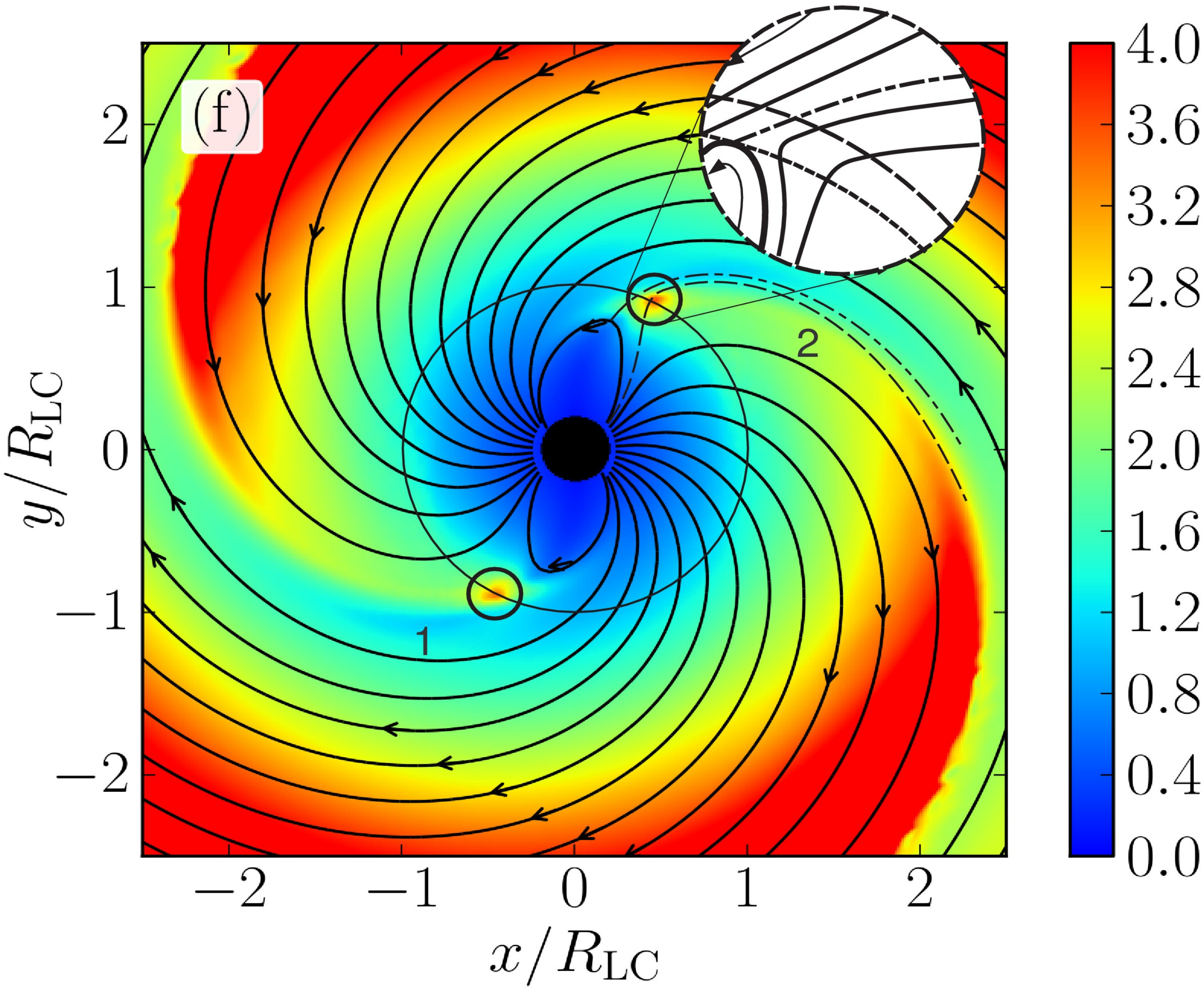


Universal law of the energy dependence on r

$$\gamma = \frac{\gamma_0(1 - r_0^2)}{(1 - r^2)}.$$

Comparison with numerical simulations

(A.Tchekhovskoy, A.Spitkovsky, J.G.Li, MNRAS, 2013)



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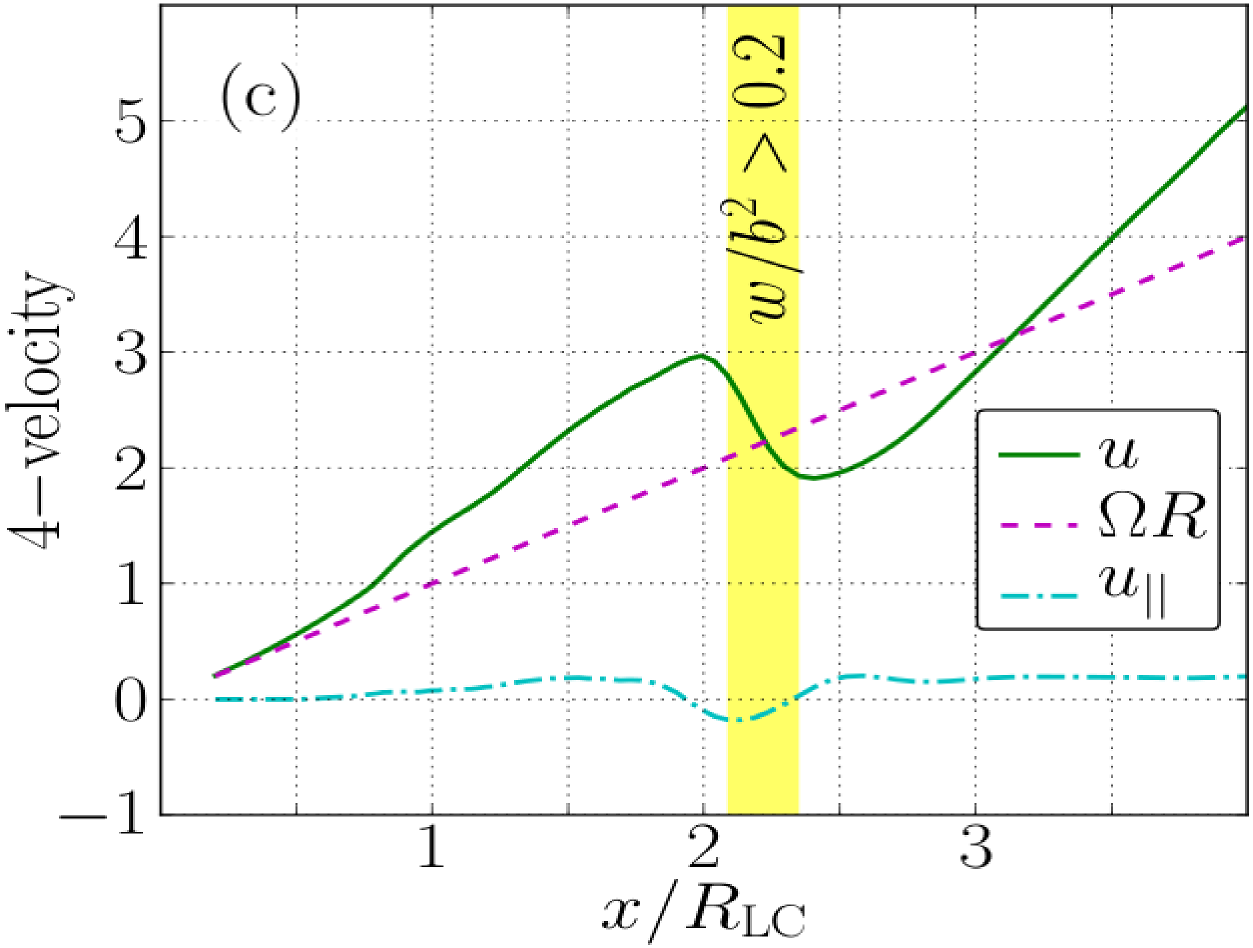
Variation of the 4-velocity along radius



Two potential cites of the centrifugal acceleration exist in the magnetospher

1. At the light cylinder but up stream the light cylinder (Small fraction of the particles can be accelerated. IC radiation of these particles is directed along the equatorial plane)

$$\gamma_{max} = 5 \cdot 10^7 (\frac{10^3}{\Lambda})(\frac{R_0}{10\mathrm{km}})^3 (\frac{33ms}{P})^2 (\frac{B}{4 \cdot 10^{12}\mathrm{G}})(\frac{\mathrm{e}_\varphi \mathrm{e}_B}{\mathrm{e}_r \mathrm{e}_B}).$$

2. Downstream the light cylinder (A few radii of the light cylinder)

Conclusion

It is still early to refuse from the centrifugal mechanism of acceleration. Gradual acceleration of the bulk motion of the plasma down stream the light cylinder can provide detected pulsed VHE radiation from the Crab pulsar like in the scenario by F. Aharonian, S.Bogovalov, D. Khangulyan, Nature, 2012