ON THE MAGNETIC FIELD CONCENTRATION IN SOLAR CORONAL LOOPS

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16th European Solar Physics Meeting (ESPM-16)
6-10 September 2021

Abstract

The equilibrium of the axisymmetric cylindrical magnetic flux rope under solar coronal conditions in the light of the paradigms of Severny and Parker connected with the existence of neutralized and non-neutralized electric currents in the solar photosphere is considered. Based on the generalized Gold–Hoyle force-free magnetic field configuration it has been shown that only the non-shielded (non-neutralized) flux ropes can provide the sufficiently strong (> 100 G) magnetic field concentration at quite small (< 10) values of the number of turns of magnetic field lines over the loop length. The formation of corona flux ropes and their MHD stability are discussed.

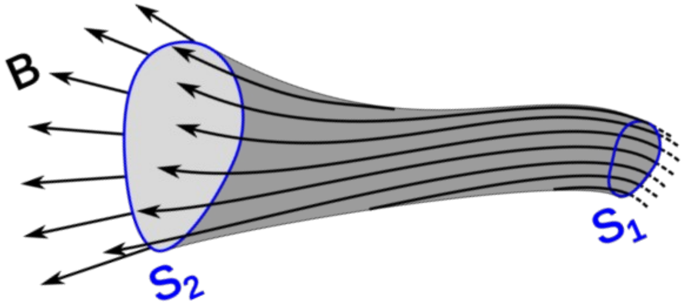
Magnetic field concentration and equilibrium of coronal loops

Photosphere

- Neutralized currents (Parker).
- Non-neutralized currents (Severny).

Corona

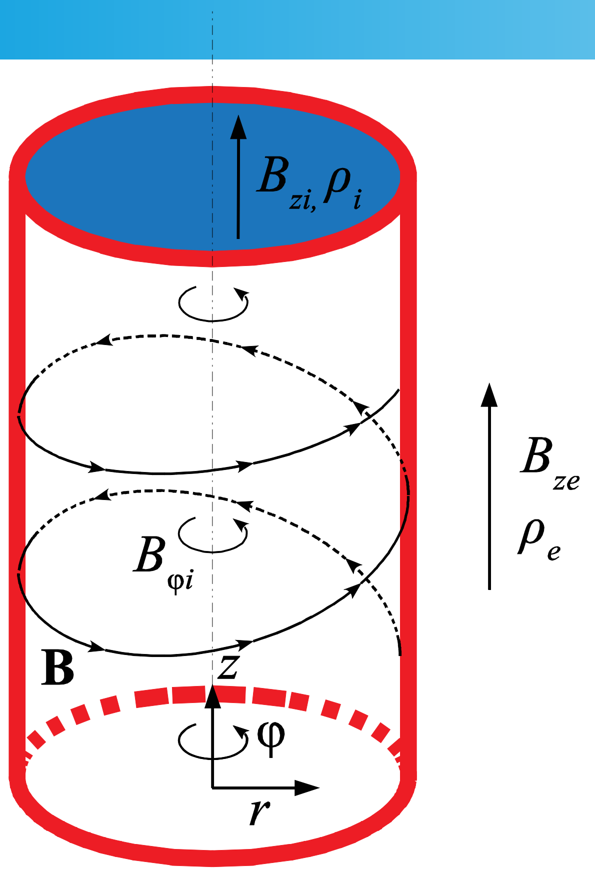
- Shielded flux ropes (external azimuthal magnetic field is zero).
- Non-shielded flux ropes (laboratory pinch).



What is a magnetic tube?

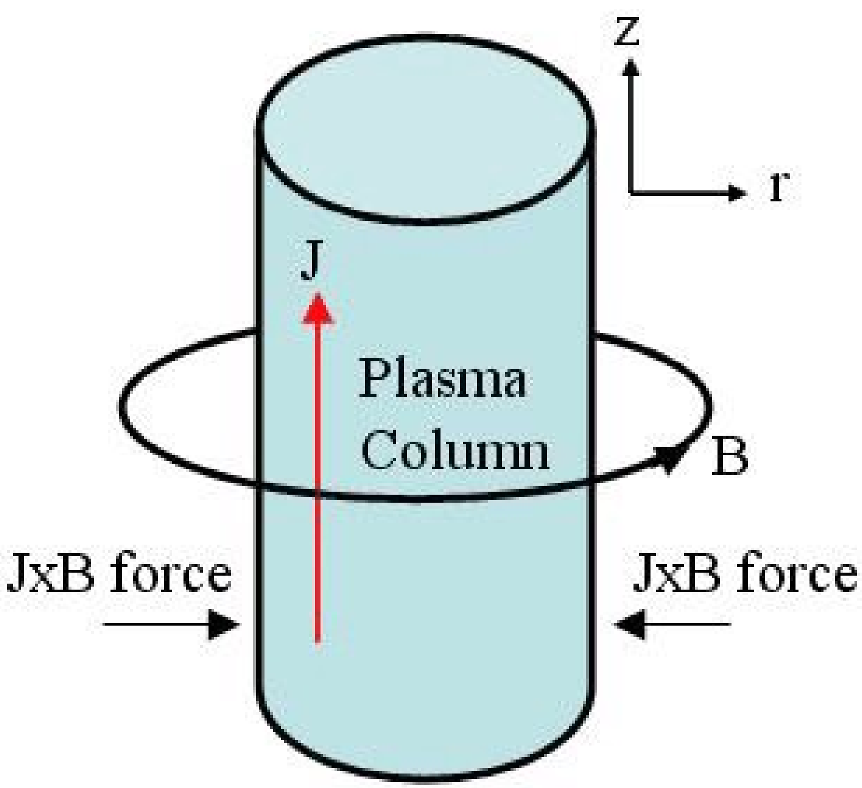
Magnetic tube – magnetic structure with cylindrical lateral surface whichis parallel to the magnetic field lines. When crossing the surface, the parameters (temperature, concentration, magnetic field strength) of the plasma can change abruptly. Boundary conditions and a magnetic tube are closely related concepts.

Models magnetic ropes



Shielded flux rope
(Parker, external azimuthal magnetic field is zero)

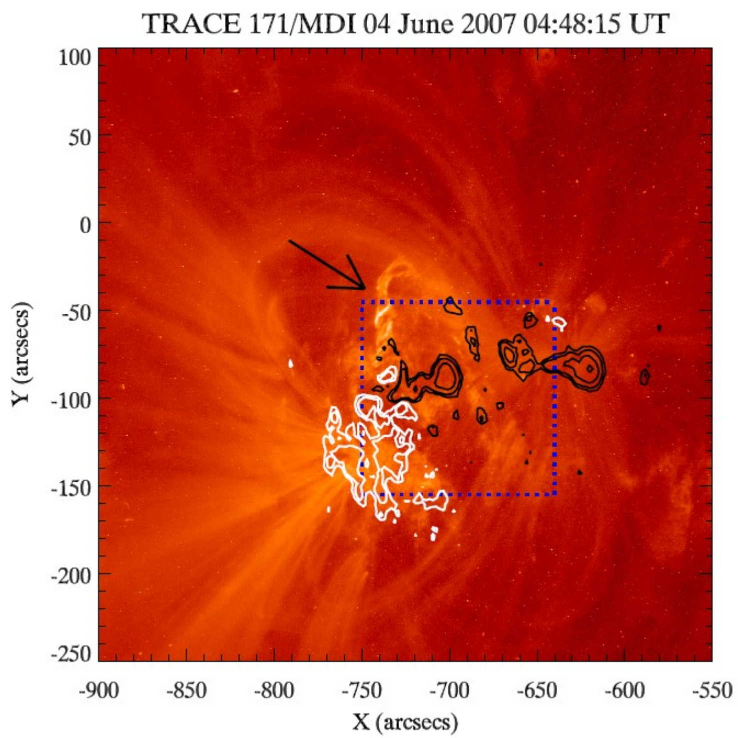
$$B_{\varphi e}(r \geq a) = 0$$
$$B_{\varphi}^2(a) + B_z^2(a) = B_{ze}^2(a)$$



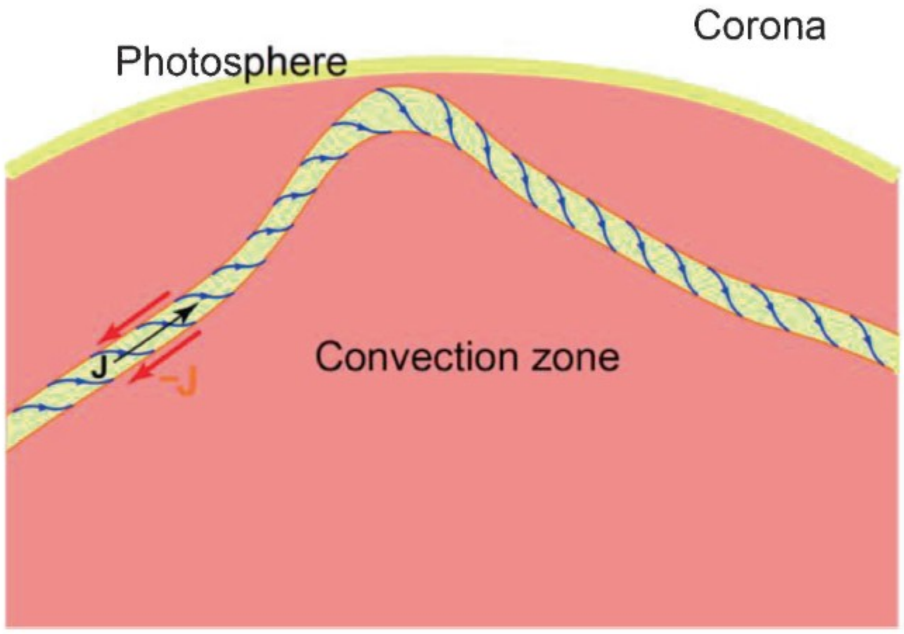
Laboratory pinch
(uncompensated current)

$$B_{\varphi e}(a) = B_{\varphi}(a)$$
$$B_z^2(a) = B_{ze}^2(a)$$

Spiral structure



Srivastava et al. (2010, ApJ, 715, 292S)



Filippov et al. (2015, JApA, 36, 157F)

Observed twist angle: $\Phi \approx 12\pi$

How tight should the magnetic flux ropes be twisted?

Magnetic field concentration

Let us consider the MHD equilibrium equation for an axisymmetric magnetic flux rope, which can be represented in the form:

$$\frac{d}{dr}\left(\frac{B_z^2 + B_\varphi^2}{2}\right) + \frac{B_\varphi^2}{r} = 0. \qquad (1)$$

Assuming that inside a flux rope of radius *a*, the square of the azimuthal component $B_\varphi^2(r) = m_\mu^2 r^\mu B_z^2(r)$, from (1) we obtain

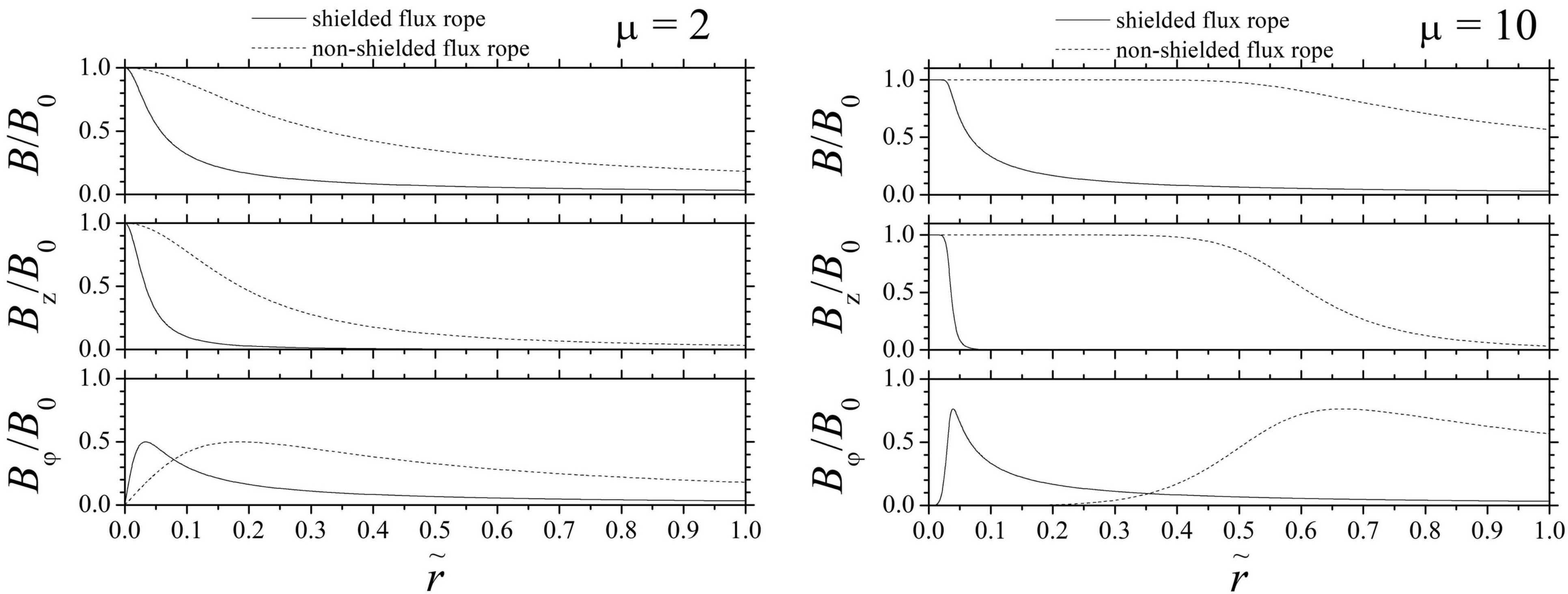
$$B_z(r) = \frac{B_0}{(1 + m_\mu^2 r^\mu)^{(\mu+2)/2\mu}},$$

$$B_\varphi(r) = \frac{B_0 m_\mu r^{\mu/2}}{(1 + m_\mu^2 r^\mu)^{(\mu+2)/2\mu}}, \qquad (2)$$

where B_0 is the magnetic field at the center of the flux rope and

$$m_\mu^2 = \left(B_\varphi(a)/B_z(a)\right)^2 a^{-\mu}.$$

Magnetic field inside the flux rope



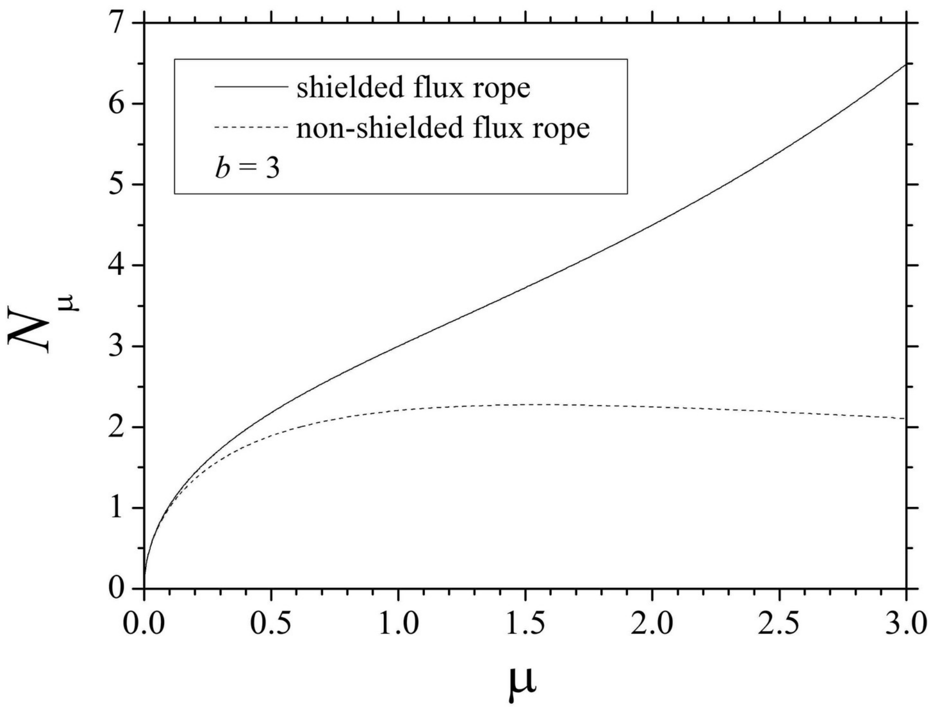
Dependence of the relative total, longitudinal and azimuthal magnetic field from the relative cross-sectional radius $\tilde{r} = r/a$ for different values of the parameter $\mu = 2, 10$.

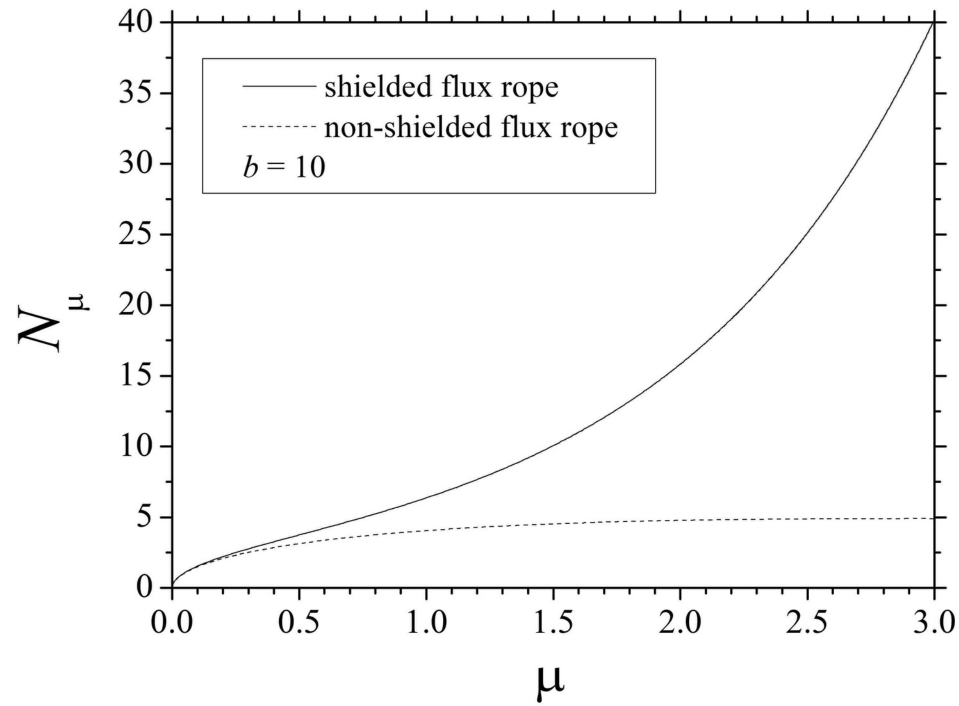
Number of turns of magnetic field lines

$$\Phi_\mu(r) = \frac{B_\varphi L}{B_z r} = m_\mu L r^{(\mu-2)/2} \qquad \mu \geq 2$$

$$\overline{\Phi}_\mu = \frac{2}{a^2}\int_0^a \Phi_\mu r\,dr \qquad b = B_0/B_{ze}$$

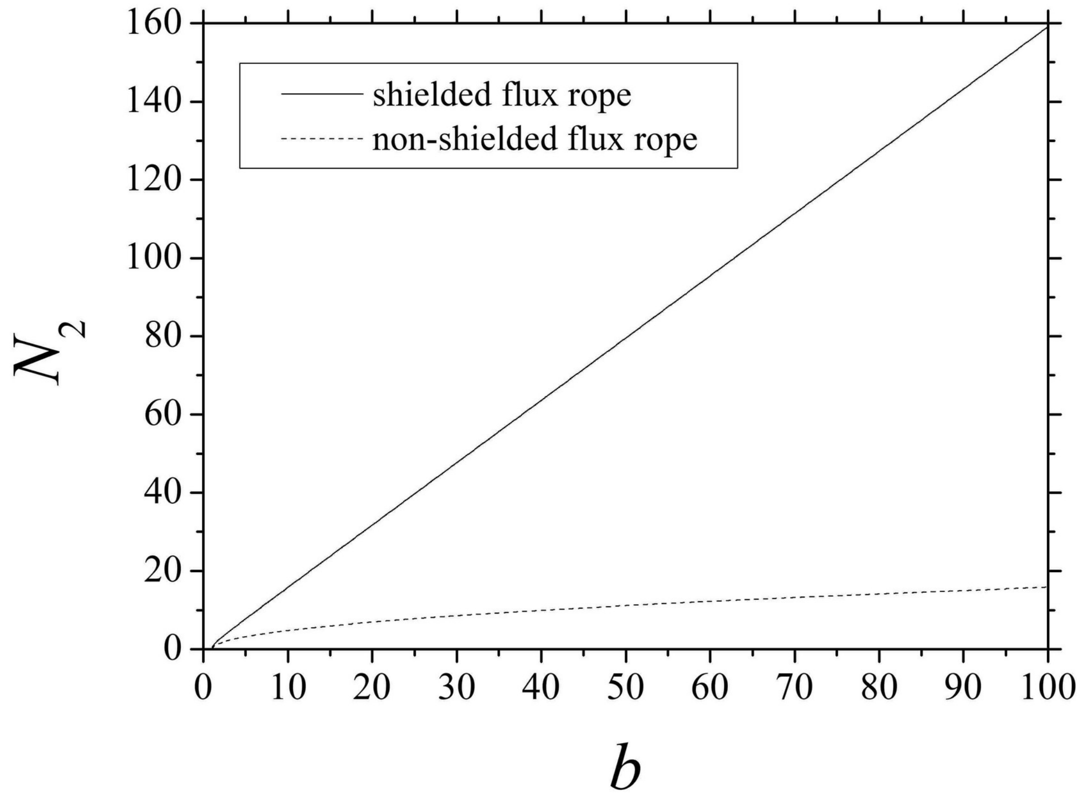
$$\overline{\Phi}_\mu = \frac{4L}{(\mu+2)a}\begin{cases}\left(b^\mu - 1\right)^{1/2}, & \text{shielded}\\ \left(b^{2\mu/(\mu+2)} - 1\right)^{1/2}, & \text{non-shielded}\end{cases}$$





Dependence of the characteristic number of turns of the magnetic field lines around the bundle $N_\mu = \overline{\Phi}_\mu / 2\pi$ on the parameter μ at various values *b*.

Gold−Hoyle solution (μ = 2)



For μ = 2, we obtain the well-known Gold–Hoyle solution (Gold T., Hoyle F., 1960, MNRAS, 120, 89).

Summary

- Shielded flux ropes weakly compress the magnetic field, but they are more resistant to helical disturbances kink instability does not work (Tsap et al., 2020, ApJ, 901, 99) .
- The concentration of the magnetic field in a laboratory pinch (circuit model of a solar flare, toroidal instability) is more suitable.