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On the magnetic skeleton of solar and stellar coronae or about possibility of coronal loop formation by the mechanical pinch effect

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Abstract. It is shown that the mechanical pinch can be responsible for the loop structure of solar and stellar coronae.

Keywords: thin structure, solar corona, stellar coronae

Space observations of the Sun in the lines of multi-ionized atoms revealed a thin loop structure of the corona. The analysis of X-ray and radio observations of active stars has shown that their coronae have similar structure as well. In this context I have referred to the paper written by S.B. Pickelner with my participation in 1959 (Pickelner and Gershberg, 1959). This paper considers a possibility of the filament formation in some cosmic medium through some mechanical pinch effect. If ends of the magnetic flux tube are connected with two more dense vortexes of some non-uniform conducting medium, then the differential rotation of these vortexes with respect to the tube axis may lead to a twisting of magnetic field lines, emergence of the azimuthal field with the pinch effect and gas compression towards the tube axis, i.e. to the formation of the filament structure. A magnetohydrodynamic calculation has been executed for the initial kinematic model in the form

$$V_\varphi = Krz, \tag{1}$$

where V_φ is the circular speed of differential rotation of some point of the tube, r is its distance from the tube axis, z is the distance along this axis and K is some constant.

Magnetohydrodynamic calculation of the model (1) consists of the combined consideration of this kinematic equation of the model with the equation of the magnetic field variation in the cylinder

$$d\mathbf{H}/dt = \mathrm{rot}(\mathbf{V} \times \mathbf{H}) + \nu_m \Delta\mathbf{H}, \tag{2}$$

where ν_m is the magnetic viscosity, and with equations of motion and continuity

$$\rho(d\mathbf{V}/dt) = -\mathrm{grad}\, p + (1/4\pi)\mathrm{rot}\mathbf{H} \times \mathbf{H} \tag{3}$$

$$d\rho/dt = -\mathrm{div}(\rho\mathbf{V}). \tag{4}$$

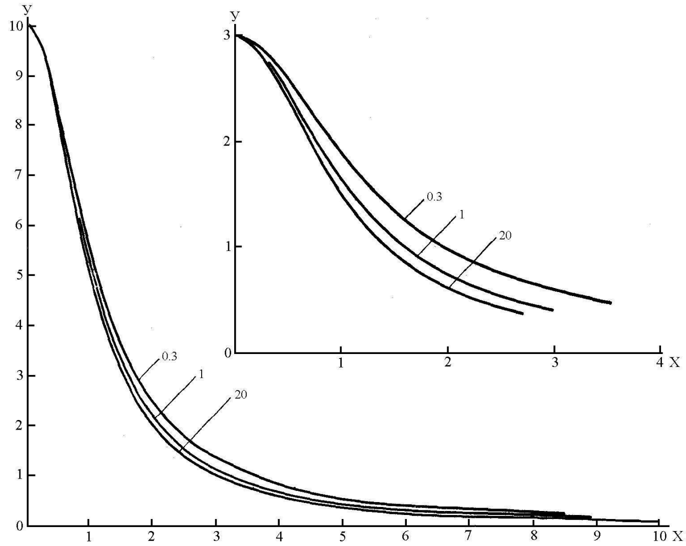

Fig. 1. Functions $y(x)$ from (Pickelner and Gershberg, 1959)

From the system of four equations for the quasi-stationary compression and negligible damping ($\nu_m = 0$), under the assumption of cylindrical symmetry and uniformity along the tube axis, in (Pickelner and Gershberg, 1959) we have obtained the following equation:

$$dy/dr = -4rP(Kt)^2y^2/[1 + 2Py(1 + K^2t^2r^2)], \quad (5)$$

where $y = \rho/\rho_0$ is the relative density with respect to its initial value and $P = H_0^2/8\pi\rho_0$ is the ratio of magnetic to gaseous pressure in the initial moment. The solution of this equation is as follows:

$$ye^{2P(1+x2)y} = y_c e^{2Pyc} = \text{const}, \quad (6)$$

where $x = Ktr$ and y_c is the y value on the axis. In Fig. 1 taken from (Pickelner and Gershberg, 1959), graphs $y(x)$ for $y_c = 3$ and 10 are presented for $P = 0.3$, 1 and 20.

Under the action of the quasi-stationary compression, i.e., at a small speed of the process of twisting power lines, the sums of gaseous and magnetic pressures on both sides of the border of the magnetic tube are identical that, according to (Pickelner and Gershberg, 1959), is possible to write as

$$y_b - 1 + Py_b^2(1 + x_b^2) - P = 0, \quad (7)$$

where y_b and x_b are the corresponding values on the border of the tube of initial radius R. The combined numerical solutions of Equations (6) and (7) for the specified values of P and y_c, inferred in (Pickelner and Gershberg, 1959), are given in Table 1.

Table 1.

	$y_c = 3$			$y_c = 10$		
P	0.3	1	20	0.3	1	20
x_b	3.5	3.0	2.7	8.5	8.9	10.0
y_b	0.46	0.40	0.37	0.22	0.16	0.10
KtR	3.4	2.8	2.5	7.5	6.9	6.8

Thus, when the density on the tube axis increases by a factor of 3, then the density on its border decreases up to 0.4–0.5 of the initial value, and when the density on the tube axis increases by an order of magnitude, then the density on its border decreases up to 0.1–0.2 of its initial value. For the ratio of the tube radius to its length 0.1 in the first case 4–6 revolutions of magnetic field lines are required and the induced field strength H_φ surpasses H_0 by a factor of 1.5–2, whereas in the second case about 10 revolutions are required and H_φ surpasses H_0 by a factor 5.

These general correlations have been applied in (Pickelner and Gershberg, 1959) to interstellar clouds HII with ionized and neutral helium, to interstellar clouds HI and to the middle chromosphere.

Magnetic viscosity is not actually equal to zero, and one has to know how small it should be to allow the discussed mechanism of loop formation to work.

Table 2.

	Interstellar clouds			Middle	Intergalactic bridges	Solar	Red dwarf
	HII	HeI	HI	chromo-	model IV	corona	coronae
	HeII	HII		sphere	in (Gershberg, 1966)		
n_i cm^{-3}	10	10	$3 \cdot 10^{-3}$	10^{10}	10^{-4}	$10^9 \div 10^{12}$	$10^{10} \div 10^{12}$
n_0 cm^{-3}	1	10^{-3}	20	10^{10}	10^{-8}		
$T\ K$	10^4	10^4	10^2	$6 \cdot 10^3$	10^6	$(1 \div 2) \cdot 10^6$	$(1 \div 2) \cdot 10^6$
$H_0\ Gs$	10^{-5}	10^{-5}	10^{-5}	3	$5 \cdot 10^{-7}$	$10 \div 1000$	$300 \div 1000$
P	0.3	0.3	15	25	0.4	0.3, 1, 20	0.3, 1, 20
ν_m	$3 \cdot 10^{14}$	$3 \cdot 10^{17}$	$2 \cdot 10^{22}$	$3 \cdot 10^{15}$	10^4	$(10 \div 3.5) \cdot 10^3$	$(10 \div 3.5) \cdot 10^3$
$R\ cm$	10^{17}	10^{17}	10^{17}	10^8	10^{19}	$(0.5 \div 2.5) \cdot 10^8$	$(0.5 \div 15) \cdot 10^8$
$U\ cm/s$	10^6	$3 \cdot 10^6$	$2 \cdot 10^5$	10^6	$2 \cdot 10^7$	10^4	10^4
R_m	$3 \cdot 10^8$	$3 \cdot 10^5$	1	3	10^{22}	$> 10^7$	$> 10^7$

For this purpose it is necessary to estimate the Reynolds magnetic number $R_m = RU/\nu_m$, and in (Pickelner and Gershberg, 1959) it has been shown that the Joule damping does not interfere with the work of the offered scheme of occurrence of filaments, if $R_m > 100$–200. Table 2 which first four columns are taken from (Pickelner and Gershberg, 1959), shows that this condition is fulfilled only in clouds HII, but is not fulfilled neither in clouds HI, nor in middle chromosphere; although in the upper chromosphere with the growth of temperature and ionization, one may expect an appreciable growth of R_m. Later I have successfully applied this model to the interpretation of intergalactic bridges of interacting galaxies (Gershberg, 1966) – see the fifth column of Table 2 with the specified values of ν_m and R_m, where n_i is the electron density, n_0 is the density of neutral atoms, H_0 is the initial magnetic field strength, ν_m is the magnetic viscosity, R is the tube radius, U is the relative rotational speed of vortexes and R_m is the Reynolds magnetic number.

The last two columns of Table 2 give data on physical conditions in the solar coronal loops and in those of red dwarfs. Values of the plasma density, magnetic field strength and magnetic tube thickness are taken from (Stepanov, 2003), temperatures are from later review in (Reale, 2014), values of the magnetic viscosity for the completely ionized plasma are calculated according to the formula by Vainstein et al. (1980) $\nu_m = 10^{13} T^{-3/2}$ cm^2/s. Recently, Mullan and Paudel (2018) have offered a scheme of the occurrence of rotation of coronal loops taking into account the statistics of granular motions at the level of loop bases. Following their estimations, these loop bases make a revolution on the Sun over time from 500 to 10^5 minutes; thus the rotation speed within an order of magnitude is estimated to be no more than 100 m/s. Then, the Reynolds magnetic number is definitely many orders of magnitude above 1, so the Joule losses do not hamper the formation of loops in solar and stellar coronae within the offered scheme.

In 2011, by means of spacecrafts measurements, Aschwanden et al. (2012) performed three-dimensional triangulatiom and magnetometric observations of nearly 500 coronal loops in four active regions of the Sun and estimated torsion parameters of their magnetic fields. These results could be considered as an argument in favor of the model of coronal loop formation described above. However, for the formation of long filaments a multi-twisted magnetic field is required, whereas solar observations give less than one complete revolution.

On the other hand, within the concept of the solar nonlinear dynamo, Kuzanyan et al. (2019) have developed a theory of the local twisting of magnetic flux tubes under the influence of the Coriolis force in the course of their emergence from the subphotospheric layers, i.e., the already twisted magnetic structures emerge; and within this theory they have presented the Maunder's butterflies for the last five cycles of solar activity.

Thus, in agreement with Parker's exact definition that «solar activity is, first of all, a result of displacement of magnetic flux tubes by convective gas motions under the solar surface and the subsequent shift of rarefied gas by magnetic field discontinuities and instabilities above the solar surface», subphotospheric plasma motions on the Sun and active stars form and twist the magnetic field; and in the twisted magnetic tubes emerging in active regions through the pinch effect, loop structures form – a magnetic skeleton of coronae.

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