IRSTI 27.35.51 https://doi.org/10.26577/phst.2022.v9.i1.03

Modeling of solar flares like an electrical circuit in plasma focus devices

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(Received 31 January 2022; received in revised form 24 February; accepted 25 March 2022)

Based on theoretical ideas about different plasma processes in Nature and Space, for example of Solar flares, a conceptual model approach is proposed based on the analogy of the flash flow with processes in an electrical circuit. Quite close in a number of parameters to the flashes are the processes of evolution of plasma objects in the "Plasma focus" setup. Based on the physical similarity of processes of this kind, patterns have been studied that make it possible to trace the change in plasma temperature depending on changes in the operating parameters of the setup. The parameters of the model corresponding to the maximum approximation to the conditions of the flash process are revealed. A program has been developed, calculations and analysis of the dependence of the plasma temperature on the parameters of the setup have been carried out: gas mass, velocity of incoming particles, load resistance in the plasma focus. It is shown that the physical model of a solar flare "Electric Circuit" can be implemented on the basis of an operating plasma focus setup, taking into account the scaling of processes.

Key words: solar flares, plasma focus, discharge current, inductance of the circuit, velocity of incoming particles, temperature, energy release, electrical circuit, pressure.
PACS numbers: 34.80.Bm, 34.80.Dp, 51.50.+v, 52.80.Dy.

1 Introduction

The processes occurring in the Sun's atmosphere attract the interest of science by their influence on a wide range of phenomena in the atmosphere and in the Earth's magnetic field. The main source of such influence is solar flares and associated eruptive prominences and coronal plasma emissions. This led to interest in the development of solar flare models. The latter is especially relevant in connection with the appearance of physical setups which allow to achieve conditions close to those that are characteristic of flash activity. The most promising from this point of view are the data obtained with the help of pulsed plasma accelerators, which are of interest not only in applied terms, but also as model setups for studying processes occurring in space objects. We propose the use of an experimental thermonuclear reactor "plasma focus" to study the nature of solar flares.

2 The theoretical part

For the empirical study of phenomena atypical for terrestrial conditions, it is promising to create physical setups that would model the behavior of an object, both in terms of physical laws and conditions that determine their evolution.

The study is about recreating a number of key circumstances associated with chromospheric solar flares using a controlled thermonuclear reactor (CTR) "Plasma Focus". The criterion for the possibility of implementing this is a comparative analysis of the physical compatibility of the complex parameters of the two objects of study. Four parameters are considered in comparison (table 1): the physical mechanism of the process, the composition of the working substance, the presence of a neutron output, parametric characteristics of the plasma generated during the process [1-3].

Table 1 – The comparison of plasma parameters in the CTR and in the solar flare

The CTR «Plasma Focus»	The solar flare
The formation mechanism	
The electric current passes through the insulator between the electrodes, forming a current-plasma sheath when a capacitor bank is discharged. Then it "collapsed" into a dense pinch formation on the contact with the substance	The convergent currents promote the compression of the photospheric plasma, and the shear currents promote the tension. As a result, the free magnetic energy is released, contributing to the flare process – the "expansion" of the plasma.
Parameters	
$I_{max}=10^6$ A, $T=10^6$ K, $v=10^8$cm/s, $n=10^{18}$cm^{-3}	$I_{max}=10^6$ A, $T=10^7$ K, $v=10^7$cm/s, $n=10^{-17}$cm^{-3}
The neutron output	
It is presented	It is presented
The working substance	
the deuterium or the mixture of deuterium-tritium	the hydrogen plasma

The proximity of the parameters of the plasma generated in the first and second cases is noticeable, which suggests the prospect of using the UTR setup to study solar flares. The analogy of the mechanism of formation of a solar flare with an electric circuit requires attention to two circumstances [4]:

- a flash is a non-stationary process, for the description of the energy release of which Ohm's law in its classical expression is not applicable:

$$j = s*E \qquad (1)$$

- the main role in the dissipation of electric current energy during a flash belongs to the neutral component of the plasma during the collision of ions with neutrals.

The basis of the physical model of the flash is the coronal magnetic arch. In the nodes of its convective structures, the bases of supergranule cells are located with a size of about R0 ≈ 30 thousand km and a convection velocity of about 0.1-0.3 km/s. The EMF that occurs during convective movements in the photosphere supports an electric current flowing in the arch from one base to another and closing in the chromosphere. At a convection velocity of about 0.1 km / s, the radius of the current tube approaches 103 km, the magnetic field at an altitude of 500 km on the axis of the arch is characterized by an induction of about 2 ×103 Gs, and the current reaches 3 ×1011 A. The inductance of the arch reaches a value of the order of 10 Gn, the current energy in the circuit reaches values of the order of 5×1022 – 5 ×1024 J [5-7]. The latter determines the energy release of the flare associated with the grooved instability of the chromosphere (Fig. 1).

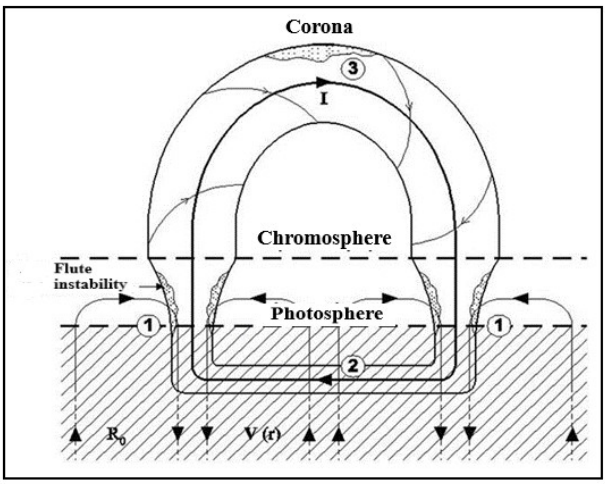

Figure 1 – Structure of the pre-flare coronal arch with current

The formation in question has a resistance R, an inductance L, and a capacity C. Then the current fluctuations in the arch can be described in the language of an RLC circuit with a capacity depending on the magnitude of the electric current according to the law:

$$C(I) = \frac{\pi * a^4 * \rho}{l * I^2} \quad (2)$$

where p is the plasma density, a is the radius of the tube, l is the length of the arch. The oscillation period determined by formula:

$$P = 2 * \pi\sqrt{L * C(I)} \approx 10 l I_{11} C \quad (3)$$

The latter ratio makes it possible to estimate the magnitude of the electric current in the flash by the period of plasma oscillations.

Since the "plasma focus" setup is an electrical circuit, the law of conservation of energy will be written in the form:

$$CU^2/2 = mv^2/2 + 3Rm/2M \quad (4)$$

where m is the mass of the plasma clot, v is its velocity.

In experiments on the UTR setup, the value of 3Rm/2M is close to one. The change in the velocity of particles occurs according to a well – known law:

$$v = v_m \cdot (1 - e^{-\frac{t}{\tau}}) \quad (5)$$

where τ=R*C.

Substituting the value (5) into (4) and expressing T, we obtain a formula for estimating the temperature:

$$T = \frac{C \cdot U^2 - m \cdot v_m^2 \cdot (1 - e^{-\frac{t}{\tau}})^2}{2} \quad (6)$$

3 The experimental part

This makes it possible to trace the change in plasma temperature depending on the change in the setup parameters and determine the parameters that allow achieving the maximum approximation to the physical parameters of the flash plasma.

According to formula (6), calculations of the dependence of the plasma temperature on the mass of the gas, the velocity of the particles and the parameters of the UTR "Plasma focus" were carried out, the results of which are presented in Figures 2 and 3.

An increase in the resistance value of the setup leads to a decrease in temperature by about 1.5 times, which brings its value closer to the real parameters of the surface temperature of the Sun. Then the influence of pressure in the plasma focus on the value of particle velocity is considered. The obtained results are shown in Figure 4.

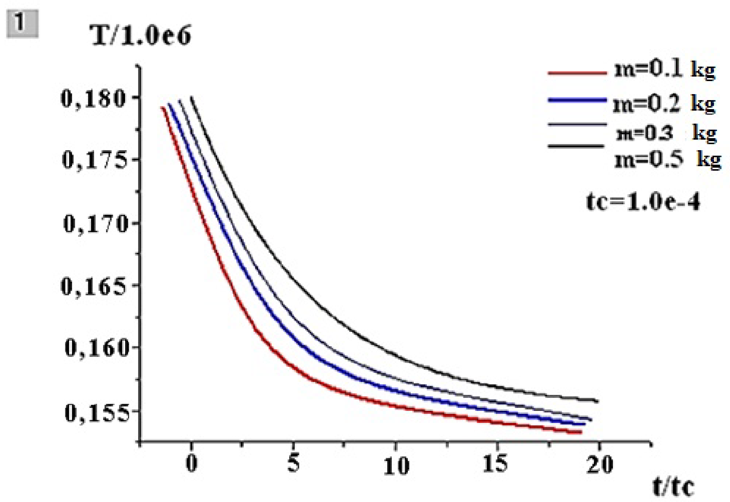

Figure 2 – The dependence of the plasma temperature in the flash model on the mass of the gas. The range of gas mass change corresponds to the setup

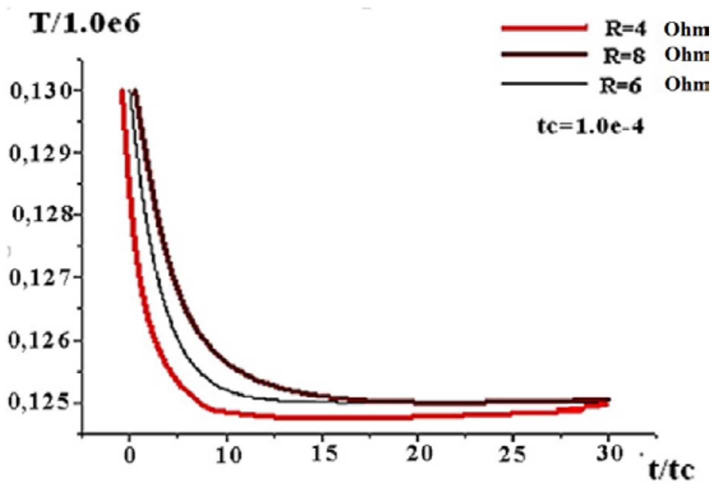

Figure 3 – Temperature dependence on setup's parameters

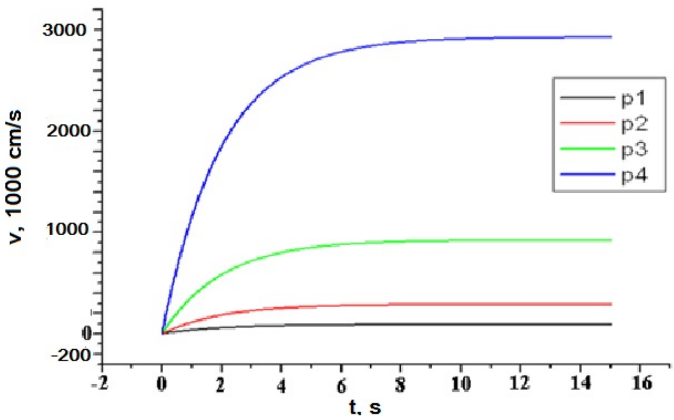

Figure 4 – Dependences of the plasma clot velocity on the pressure

The value of the velocity in all cases increases smoothly, reaching saturation, like plasma particles in a solar flare, where particles due to Joule heat gradually increase the speed and at the moment of the explosive process reach a value that allows them to fly out of the Sun.

On the basis of the obtained data, the dependence of the plasma clot temperature on the velocity of particles interacting with each other was modeled. The results are shown in Figure 5.

As can be seen, the temperature output strongly depends on the velocity of the incoming particles. The optimal value is considered to be the velocity case V_4, corresponding to the minimum pressure in the plasma focus.

Since the plasma focus is similar to an oscillatory circuit, scaling of the real flash and the size of the plasma focus was used to idealize the flash model in the setup. As noted, in order to obtain a flash in the "electric circuit" model, the resistance value must be close to zero, which corresponds to the opening of the circuit and a short circuit, and the inductance of the model must be at least 10 Hn, which is not feasible in real conditions. Taking into account the fact that the aim was to study the physical parameters of the plasma focus for modeling a solar flare, a standard value of the inductance of the plasma focus coil of the order of 10^{-9} Hn was used [8-10]. As a result, the dependence of the current strength on the resistance value of the circuit is shown in Figure 6.

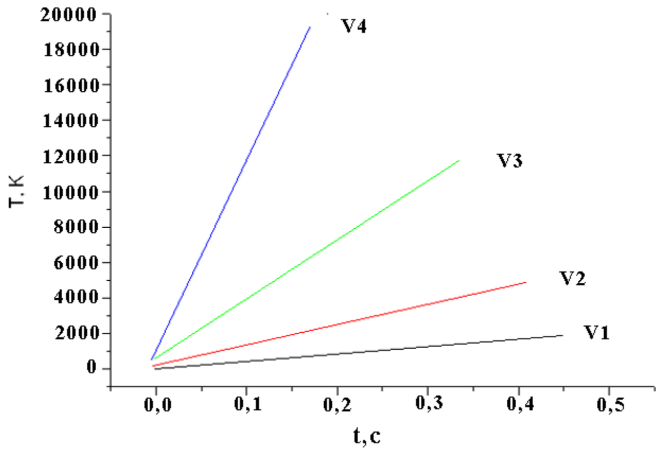

Figure 5 – Dependence of the plasma clot temperature on the velocity of the incoming particles (v_1=1000 m/s, v_2=2000 m/s, v_3= 8000 m/s, v_4=28000 m/s).

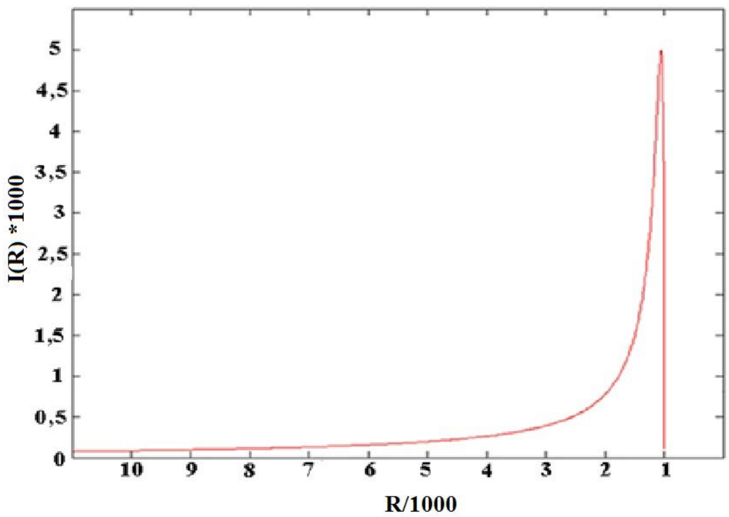

Figure 6 – Dependence of the current strength on the value of the circuit resistance.

Here, a change in resistance to zero leads first to a sharp increase in current, and then to a decrease in its value – the opening of the current, this moment corresponds to an explosion in the current layer or a short circuit situation in the circuit. Changing the inductance value in the coils by 3 orders of magnitude leads to a decrease in the maximum current by 2 times and an increase in the resistance in the circuit by an order of magnitude. Figure 6 shows a graphical view of this situation. There is no abrupt termination of the current, but there is a gradual zeroing of its value, which confirms the analogy of the plasma focus with a solar flare, where there is a gradual decline in energy output, with a series of successive weakening flashes. Calculations for the dependencies shown in Figures 5 and 7 were carried out according to the formulas:

$$I = \frac{\mathrm{E}}{\sqrt{(\mathrm{R}*f)^2 + (\omega*\mathrm{L} - \frac{1}{\omega*\mathrm{C}})^2}} \quad (8)$$

$$f = \frac{M*V*p}{R*T} \quad (9)$$

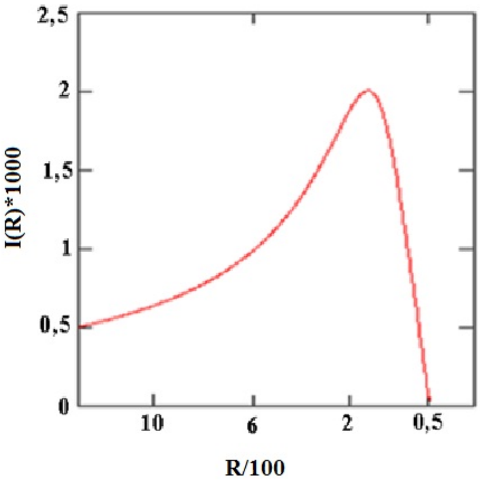

Figure 7 – Dependence of the current strength on the parameters of the circuit

Analysis of the consideration of various situations in the "electric circuit" model, expressed in changes in the parameters of the setups: a change in the resistance in the plasma focus, the amount of working substance and a change in the velocity of the incoming particles, the results are obtained that constitute an idealized model of a solar flare. This conclusion is based on a comparative analysis of data obtained from the RHESSI satellites and processed by specialists of the V. G. Fesenkov Astrophysical Institute and presented in Figure 7 [11-15].

The figure highlights three areas (time intervals are counted by the plasma focus) from 0 to 7 seconds, from 7 to 25 seconds and from 25 seconds to 32 seconds. The best matches of theoretical and real results are observed here. Although values differing in name are compared, however, both the temperature index and the value of the current strength are directly related to the energy output. Since the task of the study was to search for processes similar to natural ones and to prove the possibility of studying solar flares at the Plasma Focus setup, the comparison of these parameters is legitimate.

It should be noted that the average period of processes occurring in the area of a real flash is 65 seconds, and in the Plasma focus is 10 microseconds. From here it is not difficult to get the value of the so-called difference coefficient 65 * 105. Since the size of a standard plasma focus is about 1 meter, multiplying the difference coefficient by the length of the plasma focus, you can get an approximate size of a solar flare of about 6.5 thousand km, which is quite consistent with the length of the average arch 10^{10} cm.

In addition, we compared the results obtained from solar activity from November 2 to 4, 2003, presented in Figure 9, part a, and the theoretical dependence of the current strength on the changing resistance in the plasma focus [16]. The left side of the figure shows the energy spectra for ions of four substances H, He, O, and Fe in the preflare and flare fluxes of the events in 2003. Since in our model the working substance in the plasma focus was deuterium, in that way we compare the curve corresponding to hydrogen. As we can see, that at 8 a.m. on November 2, the value of hydrogen particles (middle part of the graph) per cm^2 fluctuates in the region of 10, at 21.00 p.m. this value changes to 10^0 and the value was 10^{-1}at 3 a.m. on November 4. It indicates a gradual accumulation of energy and the formation of a maximum at a minimum value of the matter’s ions per unit area, which can be explained by the "flute instability" of the solar flare model "electric circuit", which we have discussed it above.

At the same time, by idealizing the processes occurring in the plasma focus, results were obtained that are close to real data in that a change in the amount of the working substance makes it possible to obtain a maximum (short circuit) of the current strength [17-19].

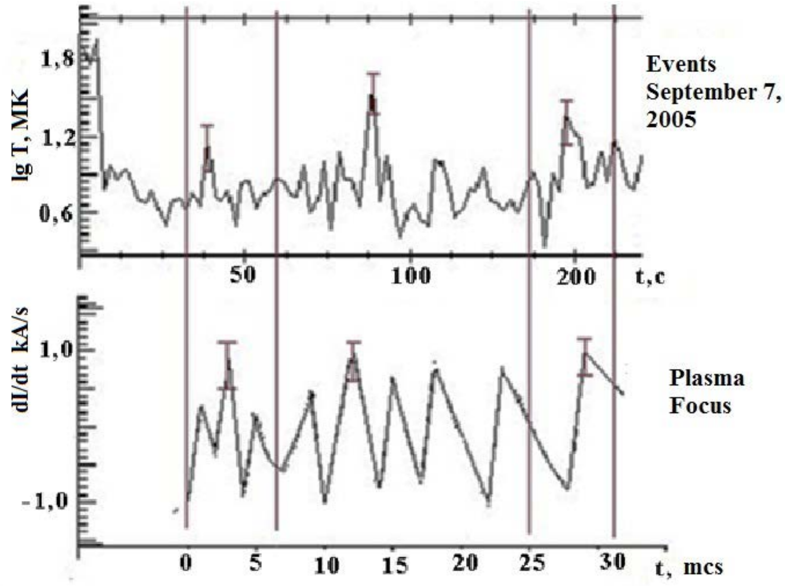

Figure 8 – The logarithmic dependence of the solar flare's temperature on September 7, 2005 and the oscillogramme of the derivative of the plasma focus current.

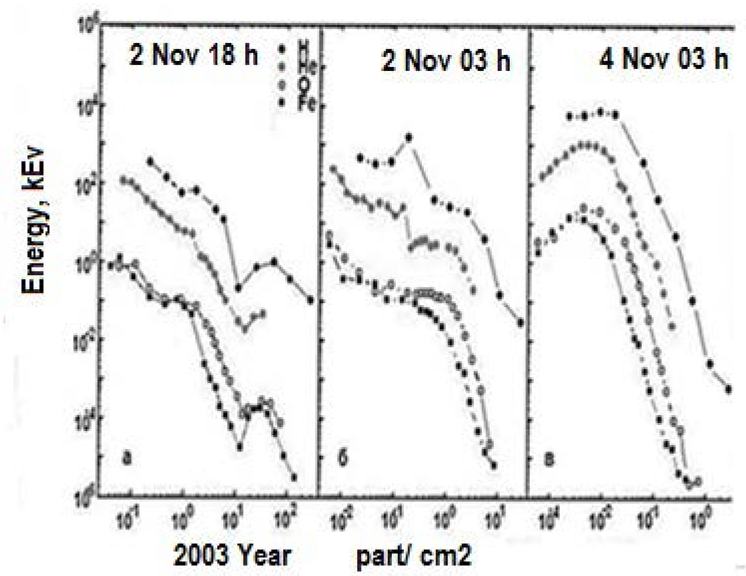

Figure 9 – The energy spectra of substances in flare flows on November 2-4, 2003 and the dependence of the current strength on the parameters of the oscillatory circuit.

The estimation of the proximity of the presented processes is obtained as a result of the conversion of the maximum current value into the electronic temperature, according to the formula

$$T = \frac{I^2}{2\pi c^2 a_1^2 k n_e} \quad (10)$$

we obtain the value of temperature about 10^6 K, while the energy value can be rounded off such as 1eV≈10^4 K. Then the final value will correspond to an energy of 0.1 keV, the difference coefficient is 10^4, such discrepancy can be explained by the scaling of processes, but there is tracedvisually the similar morphology of accumulation processes and the energy release in both processes.

4 Conclusions

In that way, we can conclude that the physically conceptual model of the solar flare "electric circuit" has found its implementation on the basis of the PF, taking into account the scaling of the flare process to the real PF setup. As a result of the simulation, the data were obtained that do not contradict the real ones and have a relative coincidence with the non-stationary processes, the processes of the formation of an energy surge.

Acknowledgements

This research has been funded by the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan (Grant No. AP15473243).

References

1. E.C. Hagen, D. Lowe, R. Obrien at al. PPPS-2013: Fast framing camera images of neutron production cessation at high currents in a Dense Plasma Focus machine// IEEE PPPS 2013 Conf., San Francisco, California, USA. -2013. -P. 7BB1. https://doi.org/10.1109/PLASMA.2013.6634885
2. A. M. Zhukeshov, A.U. Amrenova, A.T. Gabdullina et al. A plasma formation in pulsed coaxial gun at continuously filling regime // American Journal of Physics and Applications. – 2013. – Vol. 1, No. 1. – P. 5-9. https://doi.org/10.11648/j.ajpa.20130101.12
3. E. J. Lerner, M. Syed et al. Confined ion energy >200 keV and increased fusion yield in a DPF with monolithictungsten electrodes and pre-ionization // Physics of Plasmas. – 2017. – Vol. 24. – P. 102708. https://doi.org/10.1063/1.4989859
4. A.M. Zhukeshov, B.M. Useinov, A.T. Gabdullina, et al. Investigation of diffusion processes at metal target irradiation by pulsed plasma flow // Proc. of 21st International Symposium on Heavy Ion Inertial. July 18-22, 2016, Astana, Kazakhstan.
5. A. Zhukeshov, A. Amrenova, A. Gabdullina, et al. Pulsed plasma accelerator for steel samples surface modification // Thes. of 43 Int. Conf. IEEE ICOPS/ june 19-23, 2016, Banff, Canada. -P.1.
6. S. N. Polukhin, A. M. Dzhamankulov, A. E. Gurey et al. Measurement by the laser-optical method of the velocity of plasma jets generated in a kilojoule plasma focus for various gases // Plasma Physics, -2016. -Vol. 42. -No. 12. -P. 54–60 (in Russian).
7. A.N. Mayorov, V.Ya. Nikulin, A.V. Oginov et al. Investigation of axial plasma flows in a PF-4 plasma focus facility // P.N. Lebedev Institute of the Russian Academy of Sciences. –2015. – No. 7. – P. 3-13. (in Russian).
8. A.M. Zhukeshov, B.M. Ibraev, Sh.G. Giniyatova, et al. Development of the discharge chamber of the experimental setup "Plasma Focus" // Bulletin of ENU, 2016, No. 2, pp. 386 – 389. in Russian).
9. V.V. Vikhrev, S.V. Suslin. Jet formation in the plasma focus // Proceedings XLII Int. Zvenigorod Conference on Plasma Physics and Controlled Thermonuclear Fusion, 2015, p. 180. (in Russian)
10. B.B. Mikhalyaev, M.S. Ruderman, E. Naga Varun. Fast sausage solitons and super nonlinearity in coronal loops // Geomagnetism and Aeronomy. -2016. -Vol. 56. -№ 8. -P. 1040. https://doi.org/10.1134/S0016793218070149
11. Myachin D. Yu. "Structure and development of non-spotted solar flares": dissertation of Can. Phys.-Math. Sciences. Irkutsk, 2015. 214 p. (in Russian)
12. V. Abramov-Maximov, V. Borovik, L. Opeikina, A. Tlatov. Peculiarities of the development of active regions on the Sun prior to strong X-class flares: Joint analysis of data from the RATAN-600 radio telescope and SDO space observatory // Solar. Phys., -2015. -Vol. 290. -P. 53. https://doi.org/10.1134/S0010952514010018
13. A.A. Soloviev et al. Proceedings of Conf. SSZF-2017 (this collection), GOI RAS, 2017. (in Russian)
14. N. Mittal et al., On the statistical characteristics of radio-loud and radio-quiet halo coronal mass ejections and their associated flares during solar cycles 23 and 24 // New Astronomy. – 2016. – Vol. 47. – P. 64-80. https://doi.org/10.1016/j.newast.2016.02.004
15. V. Abramov-Maximov, V. Borovik, L. Opeikina, et al. Dynamics of microwave sources associated with the neutral line and the magnetic-field parameters of sunspots as a factor in predicting large flares // Solar Physics. -2015. -Vol. 290. -P. 53–77. https://doi.org/10.1007/s11207-014-0605-8
16. V.M. Bogod, L.V. Yasnov. Determination of the structure of the coronal magnetic field using microwave polarization measurements // Solar Phys., -2016. -Vol. 291. -P. 3317–3328. https://doi.org/10.1007/s11207-016-0936-8

17. L. Soto et al. Characterization of the axial plasma shock in a table top plasma focus after the pinch and its possible application to testing materials for fusion reactors // Physics of Plasmas. – 2014. – Vol. 21. – P. 122703. https://doi.org/10.1063/1.4903471

18. P.V. Strekalova, Y.A. Nagovitsyn, A. Riehokainen, et al. Long-period variations in the magnetic field of small-scale solar structures // Geomagnetism and Aeronomy. – 2016. – Vol. 56. – P.1052–1059. https://doi.org/10.1134/S0016793216080211

19. A.G. Tlatov, N.N. Skorbehz, V.N. Ershov. Numerical processing of sunspot images using the digitised long-term archive of the RGO observatory // AIP Conference Series. – 2016. – Vol. 504. – P. 237.