A new hypothesis of sunspot formation

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Abstract

The process of sunspot formation is considered with the account of heat effects. According to the Le Chatelier principle, a local overheating must precede to the cooling of solar surface in the places of sunspot formation. The sunspot dynamics is a process close to the surface nucleate-free boiling in a thin layer with formation of bubbles (or craters), so we focus on the analogy between these two processes. Solar spots and surface nucleate-free boiling in a thin layer have similarities in formation conditions, results of impact on the surface were they have been formed, periodicity, and their place in the hierarchy of self-organization in complex systems. The difference is in the working medium and method of channelling of extra energy from the overheated surface — for boiling process, the energy is forwarded to generation of vapor, and in sunspots the solar energy is consumed to formation of a strong magnetic field. This analogy explains the problem of a steady brightness (temperature) of a spot that is independent of the spot size and other characteristics.

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1 INTRODUCTION

Sunspots are observed as moderate-dark formations on the Sun surface. Today there exist many hypotheses, which are framed from different premises and able to explain different groups of features in sunspot generation and its development. Those hypotheses can be classified into several groups: hydrodynamic, magnetic, and magnetic-hydrodynamic explanations. Until 30s of the last century, the hydrodynamic and thermodynamic hypotheses had been developed; they explained generation of sunspots and their reduced temperature by adiabatic processes of gas expansion and cooling. A comprehensive review and analysis of the hydrodynamic and adiabatic hypotheses were performed by Sitnik [1].

In 1908, Hall discovered the magnetic field in sunspots. From this point, magnetic and magnetic-hydrodynamic theories have been developed. Usually they postulate an existence of general magnetic field and its amplification in the spot zones due to self-excitation processes. The general magnetic field induces the electric current in a moving ionized gas and
this induced field enhances or attenuates the primary field ("solar hydromagnetic dynamo" of "dynamo-effect"). Now the existence of a strong magnetic field is considered as a key feature of sunspots, as a primary phenomenon that controls their generation, physical and dynamic characteristics. The review and analysis of magnetic and magnetic-hydrodynamic theories is available in literature; in particular, the references to these reviews can be found in several books (Bray and Loughhead [2]; Obridko [3]) and in the later papers of other authors.

However, those theories fail to explain some observable phenomena. According to Obridko [3], there exist some difficulties concerning energy transfer in a spot and problem of sport brightness (temperature). The generated spots with penumbras have a universal brightness (temperature), which is independent of their size and other parameters. The observed brightness for spots lies in a very narrow range. The objects with a transitional brightness are unstable and decay promptly. The balance of mechanisms providing, on one hand, a reduced spot brightness, but, on another hand, a non-zero brightness, must be very strict. The fundamentals of this balance are not clear yet from the theoretical point of view. All the known mechanisms of development of the spot magnetic field (diffusion model), spot cooling, and energy transfer may provide this balance near any state; this means that we must observe a continuum of spot brightness (or its temperature).

The magnetic field plays a passive role in photosphere strata and does not participate directly in energy transfer. It makes a contribution in a change of substance distribution, and this changes the conditions for radiation energy transfer. However, significant concentrations of substance are possible that are close in temperature, because the magnetic field does not influence directly the radiation transfer. A spot is a secondary stable state of solar substance (Obridko [3]).

The phenomenon of discretization is very important in energy aspects. All stable states have different energies, and fast transitions between them are possible only if matched with release/consumption of energy that must be significant for different nonstationary phenomena in solar atmosphere.

There exists a problem of flux deficit in the spot. The problem can be formulated as follows: the spot umbra produces 15-20% of the flux generated by the undisturbed zones of the solar photosphere. Where does the rest of energy flux difference go: does it transform into other forms of energy or it is just distributed uniformly of the solar surface?

Gurevich and Lebedinsky [4, 5] were the first who put forward the idea that the radiant energy in a spot transforms into the magnetic field energy, but they did not propose any specific mechanism for that. Later, many researchers tried to explain the energy flux imbalance by energy transformation into other nontraditional forms: magnetic field, Evershed effect, motion of magnetic knots, different types of waves, etc.

Besides, we see a problem of effective conversion of heat energy into ordered mechanical energy. There exists a series of facts that indicate an intimate connection of sunspots with convection of different scales: a tendency that sunspots appear at the junctions of supergranules; a similarity in general view and properties of light elements in the spot umbra and granulation.

All the magnetic and magnetic-hydrodynamic theories use (in this or that way) the
Lenz’s rule: the induced current takes the direction that its magnetic field counteracts the changes in the magnetic flux that caused this induction. Actually, the Lenz’s rule is another presentation of the Le Chatelier principle (any system in equilibrium under external impact proceeds an automatic adjustment to compensate this impact) being applied to a particular case of electromagnetic phenomena.

The review of literature and problems concerning mechanism of sunspot formation convinced us that formation of sunspots is accompanied by heat processes that cannot be accounted by Lenz’s rule; therefore the existing magnetic and magnetic-hydrodynamic theories fail to explain the effect of constant sunspot temperature. Obviously, this consideration is incomplete and does not cover all the sides of this process. If we consider the evolution of this process with the heat aspects and Le Chatelier principle, we have to assume that a certain overheating of Sun surface stimulates the processes that apt to decrease the body temperature in the given place, and there is a need to channel out the excessive energy; it is consumed to creation of the magnetic field in the spot.

The process of liquid boiling when overheat stimulates its cooling is a close analogy to this process. Cooling takes place due to formation of a vapor bubble, and the energy goes to intensive generation of vapor phase.

In this paper we consider an analogy between formation of sunspots and liquid boiling. We want to apply the expedient that has been well-proved in physics: the knowledge accumulated in one field is being transferred to another scope of study and we check up how common are the regularities in these fields. The considered analogy must be not contrary to the results of observation.

2 OBSERVATION OF SUNSPOTS

The process of sunspot formation proceeds several stages, Obridko [3]: at first, one or several pores develop in a form of local darkening of intergranulation substance at the junctions of supergranules with the plumes over these pores. Then the elongated darkening zones of inter-granular substance develop and the pores merge. Later a patch of dark substance (or group of pores) starts condensing and the spot umbra appears. For a large spot, there can be several of those nucleate umbras. The plumes can be observed over the spots, but plumes disappear earlier than the spots dissipate.

The process of sunspot formation starts at a certain temperature and finishes when a certain level of temperature is reached, i.e. this is a threshold phenomenon. A fully developed spot has the sizes multiple to the size of supergranules, and the spots with intermediate size are usually less stable. Through the hierarchical system of self-organization of structures, it changes the regime of natural convection. The magnetic field appears before the sunspots and disappears after them.
3 OBSERVATION ON NUCLEATE-FREE BOILING IN A THIN LAYER OF LIQUID

With a growth in the heat flux, the natural convection mode is replaced by boiling mode for regular liquids. It is exactly the boiling mode that can be described by a boiling temperature (at a given pressure). Studying the mechanism of bubble formation, Moore and Mesler [6] discovered temperature pulsation under the vapor bubbles. This pulsation develops because for a boiling mode the local heat flux might be several orders higher than the general heat flux conveyed by the heating surface; and this causes a local cooling of the surface.

In the outer manifestation, the process of sunspot formation is quite different from conventional process of nucleate boiling. According to the Kutateladze’s [7] definition, the boiling is a process of evaporation in the liquid bulk. We do not see any bubbles during sunspot formation; however, the author of this paper had observed the process of nucleate-free boiling in a thin layer under vacuum - there was no bubbles, but the funnel-like and crater-like structures were formed which could move over the heating surface (Gogonin et al., [8]; Zhukov [9]; Dorokhov and Zhukov [10]). The funnel-shape structures might be formed not only in a thin layer over the heated surface, but also on a surface of overheated thick liquid layer.

The most detail study was performed with a thin oil layer with the depth of 2 mm. Two cases were studied: with the pressure above the layer equal to 200 Pa and 5-10 Pa. As the heat flux increases, two processes can be observed: they are different in manifestation, but the same in their essence. For the pressure of 200 Pa, a flash boiling took place, but it was not observed for the pressure of 5-10 Pa, but another process was observed, with the diagram depicted in Fig. 1.

Fig. 1a shows a cross-section of the convection cell and streamlines. Over the cell, a sketch of a velocity profile of vapor is depicted. The hot liquid ascends in the center of cell, and the colder liquid descends at the boundaries. On the free interface of convection cells, a temperature gradient is usually observed (Berdnikov and Kirdyashkin [11]). As the liquid is heated to the temperature close to the boiling temperature, it starts to evaporate intensively on the top interface. In this moment, the reactive force of phase transition has different magnitudes in sites with different heating. In the sites with hotter liquid it is higher, Kutateladze [7], and its action makes the layer thinner and produces a “funnel” (Fig. 1,b). Existence of “funnels” is supported by the reactive force of the phase transition.

The fact that liquid evaporation rate from the “funnel” surface is higher than in other places was evidenced by visual observation of mist jets rising from a “funnel” (it is visible in rays of light). The hotter zones have more dense population of “funnels”. This is also a place for formation of “craters” covered with ultra thin layer of oil (Fig. 1,c).

The observed processes are depicted in Fig. 2. In the place where the crater has passed, the liquid becomes colder due to intensive evaporation; first one cannot see any ordered motion of oil flow in this trace, but later convection cells develop up there. After a time, the “funnels” develop on the place of these cells. In the zones with a dense population of
“funnels”, a crater may be born again. The process tend to reproduce; and the number, size, and nucleation frequency of “craters” become higher with a growth of the specific heat flux.

But for entire range of heat fluxes, for the regime of joint existence of “funnels” and “craters”, the “craters” were always covered with an ultra fine level of oil. At last, at high specific heat fluxes, one can observe a regime with most of surface covered with “craters” and with moving narrow “bridges” of oil moving between them and providing wetting of “craters” (Fig. 2,c). At the heat flux corresponding to the beginning of this process, the “craters” are covered with an ultra thin layer of oil.

In our experiments, we measured the temperature of the heating surface with a thermocouple placed at the distance of 0.1 mm from the surface. The thermocouple readings were recorded with a plotter. The evolution of surface temperature under the 2-mm thickness oil is plotted in Fig. 3 for the specific heat flux $q \sim 10,000$ W/m$^2$ and the pressure before heating fixed at the level of 5-10 Pa. At the initial period, there is no “craters” in the oil layer and the temperature of heating surface increases by exponent (section 1-2). After $t \sim 15$ sec, “craters” develop in the layer and the surface temperature decreases (section 2-3). Since $t \sim 20$ sec, the temperature of surface remains almost constant. Since $t \sim 27$ sec, the thermocouple imbedded into the bottom demonstrates a passing of a “crater”, and temperature drops drastically (section 4-5), and then recovers (section 5-6). The next peak on this plotting corresponds to passing of another “crater” (section 6-7). After $t \sim 40$ sec, the temperature of surface again increases exponentially up to the initial level that was in the system before development of “craters” in the layer (section 7-8). The moment of passing of a “crater” over the thermocouple was tracked down by visual observations.

Since the form of event is too different from the regular boiling of liquids (e.g. no vapor bubbles), the researchers (Gogonin at al., [8]) classified this as an evaporation process, which takes place indeed. However, we can observe some features inherit to regular process of nucleate boiling:

1. With the growth of heat flux, this regime follows the regime of convective heat transfer and it is more intensive.

2. One can observe temperature pulsation of sites under the structural features of this process (“craters” and “funnels”).

3. The surface under the structural features (the basement of “craters” and “funnels”) is covered with an ultra thin layer of liquid.

Taking into consideration these features, the author of the present paper classifies the process described by Gogonin et al. [8] as surface nucleate-free boiling in a thin layer of liquid in the form of film evaporation. The essence of this mode that a liquid is being heated through a horizontal surface under vacuum. Local thinning of the layer takes place and the structures develop in the form of “funnels” (Fig. 1,b) and travelling “craters” (Fig. 1,c), which are caused by the impact of reactive force of phase transition in a non-uniform interface of liquid (Zhukov [9]; Dorokhov and Zhukov [10]).
4 COMPARATIVE ANALYSIS OF PHENOMENA

The table summarizes the comparison between formation of sunspots and process of nucleate-free boiling in a thin layer of liquid: the dynamics, conditions of formation, periodicity of processes, result of impact, place in the hierarchy of self-organization of complex systems, etc.

Table 1:

| No. | Feature or parameter                   | Sunspot                                                                 | Nucleate-free boiling                                      |
|-----|----------------------------------------|------------------------------------------------------------------------|------------------------------------------------------------|
| 1   | Dynamics of formation                  | Generation of one or several pores fringed with bright strips of flame substance. | Generation of funnels with mist rising from the surface.          |
|     |                                        | Merger of pores, formation of spot umbra, agglomeration into one big spot. | The place with highest population of funnels generates the crater. |
|     |                                        | Ascending of solar substance at the periphery of solar spots (Evershed’s effect). | The jet of vapor rises over the crater perimeter from the meniscus zone. |
|     |                                        | The spot drifts over the Sun surface.                                  | The crater travels over the heating surface.                |
| 2   | Conditions of formation                | Under vacuum                                                           | Under vacuum                                               |
| 3   | Geometry characteristics               | Pores and spots are depressions in the solar photosphere (Willson’s effect). | Funnel and craters are depressions in a thin liquid layer. |
| 4   | Sites of generation on the surface     | Produced in sites of local overheating of solar photosphere at the junctions of supergranules. | Produced in sites of local surface overheating under the layer of mineral vacuum oil in a terrestrial laboratory setup. |
| 5   | Action on the surface in the formation site | Cooling of the surface in the formation place.                       | Cooling of surface under the formation place.              |
| 6   | Periodicity                            | Periodicity feature. The period of formation is about 11 years.       | Periodicity feature. The period of formation is about several seconds. |
| 7   | Place in the hierarchy of self-organization of complex systems | Follows after the regime of natural convection.                        | Follows after the regime of natural convection.             |
Table 1: (continued)

|   | 2 | 3 | 4 |
|---|---|---|---|
| 8 | Influence of pressure | The growing pressure of magnetic field suppresses development of spot. | The growing pressure of vapor elevates the boiling temperature and facilitates the cease in boiling. |
| 9 | Influence of temperature | Threshold process, starts at a certain temperature and terminates at another temperature, e.g., balancing around a definite temperature takes place. | Threshold process, starts at a certain temperature and terminates at another temperature. |
| 10 | Working medium | Plasma | Mineral vacuum oil VM-1 |
| 11 | Channel for energy drive out from the heated surface | Energy if consumed on generation of strong magnetic field. | Energy is consumed on vapor generation. |

One can see from this compendium that the phenomena of sunspot formation and nucleate-free boiling in a thin layer have many common features: dynamics and conditions of formation, geometry characteristics, structures on the surface, influence of the formation site, periodicity. They also take the same place in the hierarchy of self-organization for complex systems (rows 1-9 of the Table). The differences are in the type of medium and the mechanism of energy channelling from the heating surface (rows 10, 11).

Pores and sunspots, as well as “funnels” with “craters” emerging during nucleate-free boiling in a thin layer, develop in places with local overheating of surface. Beyond a certain temperature (the saturation temperature) at the given pressure, the fluid transforms into a metastable state. If the system has a local overheating above the saturation temperature, this can be considered as an external impact. According to the Le Chatelier principle, any equilibrium system being subjected to an external impact, tries to change in a way that counteracts that impact. This means that in places of local overheating the structures must be formed that provide removal of heat from the heating surface and produce cooling of the heating surface. This creates pulsation in the surface temperature. The process of funnel and crater formation in nucleate-free boiling in a thin layer and creation of pores and sunspots are all the threshold-like process: it starts after exceeding of a certain temperature and stops after cooling down to a certain level, i.e., it exists in a narrow range of temperatures. The process is accompanied by energy consumption and restructuring of flow pattern. Therefore, all the surface of a spot, regardless its size, takes a uniform temperature (the model of protective shell (Obridko [3])).

The developed spot has the size multiple to the size of supergranulation, and all the sunspots with intermediate sizes are much less stable (Obridko [3]), because with a nucleation of a temperature nonuniformity inside the Sun, it is “carried away” up to the surface
due to convective flow of solar within supergranules and giant granules. While that, one or several neighbor supergranules must have a higher temperature. The solar spot cools down the surface with the size multiple to the size of a supergranules.

As it has been pointed out, the difference between the formation of sunspots and surface nucleate-free boiling in a thin layer of liquid is in the nature of working medium and the method for removal of excessive energy from the heating surface (rows 10, 11 in the Table.). Indeed, those two items are related tightly and reflect the fact that energy transformation into another form is a complex process in these processes. For liquids, the process of boiling means consumption of energy, generation of a new phase (vapor), and an increase in volume. Simultaneously, the pressure of the vapor phase grows; for vacuum boiling (explosive boiling) this fact is quite common, and a twofold pressure growth can be observed.

During a nonstationary process of bubble formation (or crater) the local temperature of the surface and liquid drops down and the volumetric pressure increases \( T_A \downarrow, P_V \uparrow \). The pressure in volume has a direct correspondence with the boiling temperature \( T_S(P_V) \) that increases with the pressure, because there exists a relation between the saturation temperature and the vapor pressure. Therefore, we have the following: \( T_A \downarrow, T_S(P_V) \uparrow \). Obviously, boiling (formation of bubbles of craters) ceases at \( T_A = T_S(P_V) \). Therefore, a decrease in the temperature of the bubble (crater) formation and pressure growth \( T_A \downarrow, P_V \uparrow \) must inhibit boiling and transfer the liquid into equilibrium state for a time (during this time, the bubble detaches or the crater collapses), and later the surface is heated up again and the process repeats.

According to the very general principle formulated by Le Chatelier, any system in equilibrium tends to rearrange for weakening of the external impact. The heating of a patch of the solar surface stimulates the process that must reduce the temperature of this patch. The same way as liquid boiling channels out the excessive energy on vapor generation, the solar energy is consumed on generation of a magnetic field (this hypothesis was put forward by Gurevich and Lebedinsky \[4, 5\]). The same as in boiling liquids, the heated surface must be cooled down, and this brings up the magnetic field pressure

\[
P_V(H) = \frac{H^2}{8\pi}
\]

That is, \( T_A \downarrow, P_V(H) \uparrow \). If we consider further this analogy, then the increasing magnetic field (similar to the vapor pressure) suppresses the growth of a sunspot. This analogy allows us to explain the accurate balancing of the temperature and magnetic field strength around certain values. However, this paper does not give the answer about an unambiguity of the \( P(H) - T \) relationship for solar substance (which is a natural consequence of this analogy). But it is a known fact that the spots can be observed on other stars, and they are similar to sunspots. Many stars have the brightness of different levels and the spot temperature and magnetic field strength must be different from value of the Sun. This creates an opportunity to generalize data in \( P(H) - T \) coordinates (magnetic field strength - brightness), but that kind of generalization is beyond the scope of this article.
5 CONCLUSION

This paper put forward a new thermodynamic hypothesis of sunspot formation. An analogy was considered between the processes of sunspot formation and phenomena of surface nucleate-free boiling in a thin layer of liquid. This hypothesis goes in line with the Le Chatelier principle and gives explanation why the brightness (temperature) of spots keeps close to a certain level.

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List of captions

Fig.1. Dynamics of “crater” formation: a - convective cell, b - “funnel”, c - “crater”.

Fig.2. Photos of the processes that were observed in the thin layer of oil VM -1 with the thickness of 2 mm: a - “funnel”; b - “crater” (shown with a cross); c - two “craters” with a bridge between them (arrow). Scale 1 cm.

Fig.3. Surface temperature pulsation during nucleate-free boiling in a thin layer at low heat flux.
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