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Revisiting the nature of dark sunspots: magneto-optical nature of darkness and heating of sunspots

Abstract

A critical analysis of the state of modern sunspot physics and the closely related physics of the sun as a whole is given. It is shown that the appearance and existence of dark and cold sunspots in the photosphere of the Sun is impossible, since this contradicts the second law of thermodynamics. The physical mechanism is described by which the magnetic field of a sunspot affects the processes of emission of light photons by the photospheric gas in the continuous spectrum of visible radiation, as a result of which it becomes dark and hot. Experimental evidence for the model of hot dark sunspots is presented. Estimates are given of the thermal power of sunspots as sources of solar wind energy and heating of the corona. A possible mechanism for the acceleration of solar wind particles in the solar atmosphere is proposed, which is based on the principle of the Laval nozzle.

Keywords: sunspot physics, second law of thermodynamics, magnetic field, photospheric gas, solar wind energy, thermal power of sunspots

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Introduction

One cannot but recognize the fact that sunspots continue to be one of the most obscure phenomena in the physics of the sun, the nature of which is still unclear. The purpose of this article is to bring some clarity to questions about the nature of sunspots and their role in the phenomena of solar activity. This clarity follows from the model of hot sunspots, which was proposed, experimentally substantiated, and described in.[1–3] Since this model is directly opposite to the generally accepted model of heliophysics of cold sunspots, all that is said below about sunspots does not correspond to or contradicts almost everything written about them in the literature. These discrepancies and contradictions are caused by the following circumstances. Despite the tremendous progress of observational astronomy, theoretical studies of the phenomena of solar activity over the past half century have not brought anything fundamentally new. The available explanations for these phenomena are, firstly, numerous, secondly, full of unsolved problems, and thirdly, so confused that only one conclusion follows from them: we do not know the true cause (or reasons) of the phenomena observed on the surface of the Sun and in his atmosphere. This conclusion indicates a crisis in modern solar physics, which cannot answer the question of why the sunspots are dark, without encountering insurmountable empirical and fundamental difficulties.[3]

According to the author, this crisis is due to the falsity of the model of cold sunspots (L. Biermann, 1941), which has long become the dogma of solar physics. The falsity of the initial ideas about the origin of sunspots gives rise to inadequate physical interpretations of the phenomena of solar activity, which determines the falsity of the results of computer simulations of these phenomena. A paradoxical situation has developed: the more thoroughly one or another phenomenon of solar activity is studied, the more complex and confusing is the question of its physical nature. As a rule, the results of another new study within the framework of the concept of cold sunspots are new questions and puzzles, and the nature of the phenomena studied remains unclear. In addition, one cannot fail to see that the false paradigm of cold sunspots voluntarily or involuntarily penetrates into all aspects of the physics of the sun. This is manifested, in particular, in the substitution of terms, in speculative and irrefutable assumptions, statements and explanations, often in the form of paralogisms and sophisms, in silence of acute issues. We illustrate what has been said with examples.

The average density of the matter of the chromosphere is hundreds of thousands of times, and the corona are hundreds of millions of times less than the density of the photosphere ($\sim 2\cdot 10^{-4}$ kg /m^3). Approximately the same order of number can be put in the ratio between the average volumetric energy densities of the magnetic fields of the chromosphere, corona and sunspots. It follows that such high-energy phenomena as solar flares [energy releases ~ (10^{22}–10^{25}) J] and emissions of matter with a mass of ~ (10^9–10^{14}) kg per se can neither occur in the chromosphere nor in the corona. But in the physics of the Sun, stable terms have become firmly established - “chromospheric flare” and “coronal mass ejection”. They indicate that flares originate in the chromosphere, and the mass is ejected from the corona. If we add to this the widespread definition that prominences are formations in the corona of the Sun, then there is almost the conviction that nothing significant happens in the photosphere. The same conclusion follows from the context of scientific articles on solar activity, which is in good agreement with the concept of cold sunspots, but is strikingly contrary to reality. The situation is about the same as if volcanologists investigated the “tropospheric eruptions” and “stratospheric emissions of ash”, completely ignoring the existence of volcanoes - the sources of these eruptions and emissions of ash.

The assumption that the driving force and energy source of the Sun’s activity is its magnetic fields has now stepped over the rank of the hypothesis and has become in fact the second (after cold spots) dogma of modern heliophysics. If we continue the analogy with volcanoes on Earth, it must be said that today its magnetic fields are considered volcanoes on the Sun. The “eruptions” of these volcanoes, that is, the processes of sudden release of magnetic field energy, initiated by the phenomenon of reconnection of their magnetic lines of force, give rise to all the phenomena of solar activity. In this case, it is believed that the energy of a changing magnetic field is transformed directly into heat, kinetic energy of matter motion and into the energy of accelerated charged particles emitting electromagnetic waves in the range from radio waves to gamma rays.

The speculativeness, as well as the incontrovertibility of such a theory of magnetic solar activity, is obvious. First, we can more or less reliably measure the magnetic fields of the Sun so far only on the surface of its spots, however, even in this case we are not able to estimate the supply of their magnetic energy. Secondly, it is practically impossible to obtain objective and sufficiently reliable data on magnetic fields and electric currents (current sheets) not only inside the Sun, but also in its atmosphere. Thirdly, the phenomenon of reconnection of magnetic fields actually exists only in theory, since it has not yet been recorded by anyone and anywhere on significant energy and spatial scales.

It follows that the physical mechanisms and dynamics of the processes of energy conversion of changing solar magnetic fields into heat, mechanical energy and radiation energy, as well as the reality of such processes inside the Sun and in its atmosphere, can only be guessed. Consequently, the key question about the source of energy that provides the observed level of activity of the Sun remains open. It is generally accepted that the temperature of the photospheric gas in sunspots is not (4000 4500) K, that is, in visible light they should be neither dark nor black, which is true, however, only for penumbra spots.

Literature data on the intensity of continuous radiation (or brightness) of the umbra of sunspots are extremely scarce, vary widely and are usually given without explanation of how they are received and what kind of intensity or brightness (visual or energy) in question. But for more than 2000 years, visual observations of the Sun indicate virtually complete darkness (blackness) of the umbra of all sunspots without exception, which objectively confirms all the latest space photographs of the Sun with high resolution. This is probably why the textbooks on astronomy and astrophysics, not to mention popular science literature, constantly assert (in all possible variations) that sunspots only seem dark to us in contrast to the photosphere, and that a solitary sunspot would glow brighter than an electric arc. This sophism has no physical content, so it is as difficult to refute it as to solitude a sunspot.

At the same time, observational facts that clearly do not fit into the model of cold sunspots are mentioned in the literature either casually or not at all, although they should be of most interest. For example, the fact that sunspots shine brightly against the background of the photosphere in ultraviolet and X-rays is not discussed in scientific articles. Meanwhile, without a clear and deep understanding of the physics of sunspots, that is, without a proper solution to the puzzle called "dark sunspots", one cannot find solutions to other problems of solar activity, just as one cannot achieve the goal by going the wrong way.

"Dark cold" and "dark hot" sunspots

It is known that the layers of the Sun located below the photosphere are not observed in any spectral region. From this fact and the fact that the sunspots glow in the X-ray wavelength range, it necessarily follows that the photospheric gas in the spots is heated to temperatures of ~ (10^6–10^7) K, since only in this case it will be a source of X-ray radiation. This means that sunspots can in no way be regions of the photosphere with a lowered gas temperature, as is affirmed in all literature. On the contrary, sunspots are the hottest areas not only in the photosphere, but also in the entire atmosphere of the sun. This fact alone removes the fundamental contradiction between the second law of thermodynamics and the recorded heating of the solar corona to temperatures of ~ 10^6 K, which should be considered as convincing confirmation that dark sunspots are really hot.

Consider two mutually exclusive sunspot models: the cold spot model and the hot spot model. Each of them should give answers to two main questions: the cold model - to the questions "why are the spots dark?" and "why are they cold?", and the hot model - to the questions "why are the spots dark?" And "why are they hot?". Since a sufficiently strong magnetic field is an attribute of all sunspots, the brief and formally correct answer to all these "why" in one and the other model is the same: visible darkness and cooling spots (cold model) or visible darkness and heating spots (hot model) are due to the magnetic fields of these spots. Consequently, only the model for which there are real physical mechanisms and processes that determine a causal relationship between the magnetic field of the spot and its darkness corresponding to this model will be real. It should be borne in mind that any theoretically possible process can be real only if there are no factors due to which its implementation is prohibited or impossible.

Here it is appropriate to give an example. From the equations of gas dynamics it follows that there must be compression shock waves (gas heating at the wave front) and rarefaction shock waves (gas cooling at the wave front). However, only compression shock waves exist in nature, while rarefaction shock waves do not exist, and it is impossible to create them, since the gas cooling process at the shock front is prohibited by the second law of thermodynamics. In the model of cold spots, the causal relationship between the magnetic field of the spot and its darkness is expressed by a simple and obvious implication: "if the spots are dark, then they are cold." The truth of this implication means that the magnetic field is responsible only for cooling the spot, and its darkening is due to the laws of thermal radiation. But in this case, the appearance of dark spots, especially those as we see them, is difficult or even impossible, since the condition of radiant equilibrium is quite well satisfied in the photosphere.

In addition, in the photosphere, the main role in energy transfer is not convection, but radiant heat transfer, which the magnetic field does not affect. Against the background of these difficulties, the question arises, not only and not so much about the efficiency of the cooling process of a weakly ionized photospheric spot gas due to the suppression of its convection by a magnetic field, but about the reality of such a process. From the second law of thermodynamics it follows that there is no natural (spontaneous) process that would cool a gas in a spot (with or without a magnetic field) below the temperature of the surrounding gas (as a result of which the spot would naturally become darker than the photosphere).

In fact, how can a gas are cooled in a spot below the temperature of the photosphere? There is only one way: by the action of a heat pump, which transfers heat from a body with a low temperature (gas in a spot) to a body with a higher temperature (gas outside a spot) due to the work of an external force. However, it is clear that under no circumstances the magnetic field of a spot can be a heat pump, even if magnetic monopoles existed on the Sun. Therefore, dark and cold sunspots are impossible, and the implication "if the spots are dark, then they are cold" is false. The fact of longevity in heliophysics of the hypothesis of magnetic cooling of sunspots indicates only how difficult it is to actually perceive and take into account the inevitable and sometimes mysterious effect of the second law of thermodynamics. For sunspots, only the implication "if the spots are dark, then they are hot" can be true, because it expresses the only possible causal relationship between the magnetic field of the spot and its darkness. Generally

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speaking, the darkness of sunspots, as well as the brightness of the visible glow of various bodies cannot be unconditionally associated with their temperature. In terrestrial conditions, many cold objects of animate and inanimate nature shine brightly in all colors of the rainbow, which does not surprise anyone, since we know that this is non-thermal radiation. Obviously, dark sunspots can also be hot if the laws of thermal radiation are violated accordingly, which in this case makes the magnetic field of the spot successful.

It is known that the continuous spectrum of the visible radiation of the Sun is responsible for the photorecombination of negative hydrogen ions (radiative free-bound transitions).The suppression of these processes by a magnetic field is the main cause of darkness and heating of the photospheric gas in sunspots.[3] In the magnetic field of the sunspot, the spin magnetic moments of free electrons and hydrogen atoms (paramagnetic particles) are oriented mainly along the field, and when these particles collide, their spin magnetic moments will almost always be parallel to each other. In a sufficiently strong magnetic field, it is precisely this circumstance that makes the photorecombination of diamagnetic negative hydrogen ions impossible. Consequently, the processes of emission of photons of visible light also become impossible. At the same time, the absorption of photons of visible light penetrating the spot from all sides, i.e., the process of photoionization of negative hydrogen ions (bound-free transitions), the magnetic field does not interfere, as a result of which the gas in the spot heats up.

Thus, the origin of dark and hot sunspots has a magneto-optical nature. This means that the appearance of the sunspot is due to the magneto-optical phenomenon, which consists in quenching by the magnetic field the intensity of the glow of the photospheric gas in the continuous spectrum of visible radiation, the energy of which is used to heat the spot. In other words, radiative free-bound transitions that occur during photo recombination of negative hydrogen ions in a magnetic field of a sunspot become non-radiative, i.e., a magnetic field dissipates the photon energy of the continuous spectrum of the visible radiation of the Sun into the energy of thermal motion of photospheric gas particles.

Magnetic field quenching of predominantly continuous thermal radiation is due to the fact that, in this case, unlike discrete radiation, the electron in the initial state is free, and the orientation of its spin magnetic moment is determined by the magnetic field of the spot, which can radically change the probabilities of optical quantum spin-dependent transitions. Since such magnetic spin effects are known and have a general character, it is possible to experimentally verify the model of hot sunspots directly in terrestrial conditions. In,[1,2] an experimental study of the influence of various magnetic fields on the intensity of the visible glow of tungsten filaments of ordinary electric incandescent lamps is described. The experiments used short unipolar magnetic field pulses with an induction amplitude of $B \leq 40$ T, differing in shape and duration (~100-250 μs), and oscillating magnetic field pulses having the form of damped sinusoids with a half-wavelength of 1-5 ms and induction amplitudes of $B \leq 12$ T. The light intensity was recorded by a photomultiplier in the direction along the magnetic field imposed on the lamp filament.

It was found that the magnetic field reduces the intensity of the glow of the lamps. Unipolar magnetic fields caused only a partial (up to ≈50% at 40 T) attenuation of light intensity. This effect was significantly enhanced with an increase in the duration of magnetic field pulses (even if its induction was significantly reduced) and reached saturation in a sinusoidal field with a half-wavelength of ≈3 ms, after which the degree of attenuation of the luminous intensity depended only on the magnitude of the magnetic field. In a sinusoidal magnetic field with a half-wavelength of 5 ms, a noticeable (recorded) decrease in the luminous intensity was observed at an induction amplitude of $B \geq 0.1$ T (threshold induction), and when induction reached $B \geq 0.6$ T (critical induction), complete quenching of the intensity was already observed visible glow of the investigated lamps. Thus, the results of this study quite convincingly confirm the model of hot dark sunspots. Especially important in this regard is the fact that the threshold magnetic field (~0.1 T), which causes a noticeable attenuation of the lamp glow, and the critical magnetic field (~0.6 T), which already causes complete quenching of the visible radiation of the lamp filaments, practically correspond to the values of the induction of the minimum and maximum magnetic fields in sunspots. Of course, we can assume that this is a coincidence. However, with a much greater probability it can be argued that this fact indicates a close "relationship" between the mechanisms of visible light emission by the tungsten filament and the sun's photospheric gas. In essence, both the photosphere and the hot tungsten represent a low-temperature plasma, and as sources of thermal radiation, they differ only in their temperature values.

Very little is known about the mechanism of visible light emission by tungsten, but weighty arguments can be made in favor of the "relationship" of this mechanism with the visible light emission mechanism by the Sun. Firstly, negative tungsten ions have almost the same ionization energy (0.8 eV) as negative hydrogen ions (0.75 eV). Secondly, the presence of negative ions in the tungsten lattice is confirmed not only by the high selectivity of tungsten radiation in the visible spectrum, but also by the results of experimental studies of thermionic and field emission of tungsten [4, Chap. 9]. We note that the selectivity of tungsten radiation indicated above means that the fraction of the energy of its radiation in the visible region of the spectrum is much larger than the similar fraction in the radiation of a black body that has the same temperature as tungsten. Third, the spin states of tungsten valence electrons are strictly ordered (the spins of two 6s electrons are paired, and the spins of four 5d electrons are parallel). This means that free-bound transitions in tungsten, forming a continuous spectrum of its visible radiation, can be spin-dependent, i.e., their probabilities in a magnetic field and in its absence will be different.

In addition to the results of the above experiment, no less, if not more convincing arguments for the correctness of the hot sunspot model are those conclusions and consequences that follow from it. A correct scientific hypothesis should not only explain, but also predict empirical data. It should be stated bluntly that in the case of the model of cold sunspots, there is neither one nor the other. It seems that the only convincing evidence in favor of this model is the obvious fact of the visible dark spots, the indisputability of which became the trap into which solar physics fell. Meanwhile, the model of hot dark sunspots allows us to explain almost all the phenomena of solar activity, excluding those whose "roots" are deep inside the Sun (problems of dynamo, cyclicity, etc.). We mention only a few points of this large topic.

The hot gas of the sunspot is a hydrogen-helium plasma with an admixture of ions of other elements present in the photosphere, which can freely move only along the magnetic field directed almost vertically in the spot umbra. If we take into account that the thermal

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conductivity of the plasma in the direction transverse to the magnetic field is difficult, it becomes clear that the fluxes of heat and matter in the sunspots are directed mainly upward to the outside of the Sun. This means that sunspots are the most powerful generators of thermal energy in the entire solar system and, at the same time, the most powerful electron-proton and ion cannons. In other words, a sunspot is a giant magnetic bottle filled with hot and continuously heated plasma, the upper neck of which is open and coincides with the umbra of the spot.

The energy luminosity of the photosphere is ~$6.2 \cdot 10^7$ W/m^2, of which ~$2.7 \cdot 10^7$ W/m^2 accounts for visible radiation. This is the surface density of the flow of thermal energy emerging from the umbra of the sunspot. A relatively small sunspot with an umbra surface area of 100 ppm of the solar hemisphere (1 ppm ≈ $3 \cdot 10^6$ km^2) creates a flow of thermal energy with a power of ~$8 \cdot 10^{21}$ W, which is approximately equal to the solar wind power of the Sun. Note that approximately the same power is required to heat the corona. The existence of a solar wind means that the component particles of this wind must either fly out from the umbra of spots with velocities far exceeding the second cosmic velocity for the Sun (618 km/s), or they will somehow accelerate in the atmosphere of the Sun, since the thermal velocities of protons reach values ~600 km/s only at temperatures ~$2 \cdot 10^7$ K. A possible mechanism for accelerating solar wind particles can act on the basis of the principle of operation of the Laval nozzle, which is formed in the photosphere by a magnetic spot bottle (confuser), and in the solar atmosphere by a radial magnetic field extending into the corona (diffuser). If the corona gas is heated to ~ $2 \cdot 10^6$ K, then the plasma in the spot must be heated to much higher temperatures. In this case, due to the thermal energy of the plasma in the magnetic bottle, the required speeds of the particles of the solar wind can be achieved.

Conclusion

The real volcanoes in the sun are sunspots. These sunspots, volcanoes, unlike earthly ones, are constantly active and never "sleep". Sunspots arise and exist only in those regions of the photosphere where sufficiently strong magnetic fields appear and exist, but the main "engine" and conductor of the grandiose processes of solar activity is the high temperature of the spots, that is, their thermal, but not magnetic energy. The dark spot visible on the surface of the Sun is just the vent of a solar volcano. It is possible that inside the Sun in areas where strong magnetic fields are present, closed sunspots appear that do not have a direct exit to the surface of the Sun. The model of hot dark sunspots allows us to explain many phenomena of solar activity, which previously seemed mysterious. However, this raises a number of new questions, the answers to which are still unknown.

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