Research Article

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Revisiting the nature of dark sunspots: the sun as a heat engine

Abstract

This work is a continuation of the author's studies,[1,2,3] related to the elucidation of the physical nature of dark sunspots. They showed that the appearance of cold sunspots, the temperature of which is below the temperature of the photosphere, is incompatible with the second law of thermodynamics. Sunspots in the Sun's photosphere can only be hot. This article provides a thermodynamic analysis of the work of the Sun as a heat engine. It is shown that sunspots are dissipative structures that spontaneously appear in the photosphere of the Sun and ensure its viability as a source of optical radiation. Sunspots play the role of a cooler for the sun's global heat engine, and without them its radiant glow would be impossible, just like the operation of any heat engine without a cold heat sink. In addition, it is shown that all the phenomena of solar activity are caused by the operation of the photospheric heat engine of the Sun, in which sunspots are the source of heat.

Keywords: sunspot physics, second law of thermodynamics, heat engines, solar radiation, solar wind

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«The law that entropy always increases – the second law of thermodynamics – holds, I think, the supreme position among the laws of Nature. If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations – then so much the worse for Maxwell's equations. If it is found to be contradicted by observations – well, these experimentalists do bungle thinks sometimes. But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation. This exaltation of the second law is not unreasonable.»

Eddington, A. S. The Nature of the Physical World (Gifford Lectures). Brooklyn: AMS Press, 1927.

"I was naïve enough to believe that such a pseudo-science would die by itself in the scientific community, and I concentrated my work on more pleasant problems. To my great surprise the opposite has occurred: 'merging' pseudo-science seems to be increasingly powerful. Magnetospheric physics and solar wind physics today are no doubt in a chaotic state, and a major reason for this is that part of the published papers are science and part pseudo-science, perhaps even with a majority in the latter group."

H. Alfven, Keynote Address, Proceedings from NASA Workshop on Double Layers, Huntsville AL, March 17-19, 1986.

Introduction

From a thermodynamic point of view, the unevenly heated plasma ball of the Sun, containing in its core a thermonuclear reactor - a source of thermal energy, which in the photosphere is converted into electromagnetic energy of solar radiation and into mechanical energy of the solar wind and other phenomena of solar activity - is a heat engine. This means that all processes of converting the thermal energy of the Sun's core into other types of energy must obey the second law of thermodynamics, which establishes the impossibility of fully converting a given amount of heat into work, by which, in the general case, it is necessary to understand not only mechanical interaction, but also any other non-thermal interaction. Before considering the Sun as a continuously operating heat engine, it is necessary to emphasize the principle of operation and the features of the functioning of any heat engine. They boil down to the presence and interaction of three elements: a hot source of heat - a heater with temperature T_1, a working body (gas) and a cold receiver of heat - a cooler with temperature $T_2 < T_1$. To simplify the analysis of the operation of a heat engine, it is usually assumed that the heater and cooler have large heat capacities and their temperatures T_1 and T_2 do not change during the transfer and reception of heat. The heater gives off a certain amount of heat Q_1 to the working body, part of which it converts into mechanical work $\dot{A}$ (or into any other non-thermal form of energy), and the working body must certainly transfer the rest of the heat $Q_2 = Q_1 - \dot{A}$ to the cooler. The need for a cooler is dictated by the second law of thermodynamics, according to which it is impossible to create a heat engine in which all the heat received from the heater would be converted into work. A heat engine is capable of performing work due to heat only in the presence of a heat flux generated by a spontaneous transfer of heat from the heater to the cooler through the working body, when the transfer of part of the heat to the cooler is inevitable. The absence of a cooler is equivalent to a lack of heat flow due to the equalization of the temperatures of the heater and the working body. In short, a heat engine can arise, be created and function only where there is and is constantly maintained a temperature difference between a heater and a cooler.

The principle of operation of all heat engines without exception (Carnot's principle) can be expressed by the inequality

$$\dot{A} \le \frac{T_1 - T_2}{T_1} Q_1, \qquad (1)$$

where the equal sign refers only to a reversible Carnot heat engine, $\dot{A} = Q_1 - Q_2$ is the amount of work performed by the heat engine, Q_1 is the amount of heat received by the working body from the heater, Q_2 is the amount of heat given by the working body to the cooler, T_1 and T_2 are the absolute temperatures of the heater and cooler. Since all thermal processes are irreversible, it follows from (1) that the functioning of a real heat engine is possible only if the inequality

$$\frac{Q_1}{T_1} < \frac{Q_2}{T_2}, \tag{2}$$

The physical meaning of which is unambiguous: the decrease in the entropy of the heater, due to the transfer of heat Q_1 to the working body at a temperature T_1 for a certain time, must be compensated in excess by the increase in the entropy of the cooler due to the transfer of heat Q_2 to it by the working body at the temperature T_2 during the same time. Inequalities (1) and (2) determine the efficiency of converting thermal energy into any other types of energy, and they cannot be violated in any heat engine.

The sun as a natural heat engine

Obviously, the heater of the heat engine of the Sun is its core, which has a thermonuclear reactor, and the working body is the rest of the Sun, which has no sources of thermal energy. The overwhelming share of this working body in terms of its mass and volume, which includes the radiation and convective zones of the Sun, plays mainly the role of a coolant that supplies the thermal energy of the core to the photosphere, the active part of the working body. It is in the photosphere that the most grandiose in the solar system and the most important physical phenomenon for us takes place - the transformation of the thermal energy of the sun's core into electromagnetic energy, strictly distributed over the photons of solar radiation, which carry it into space evenly in all directions. Such a transformation does not contradict the law of conservation and transformation of energy, if only the total energy of all photons emitted per unit time does not exceed the amount of thermal energy supplied to the photosphere during the same time. Since it follows from observations that the surface temperature of the Sun is $T_{phot.} = 6000 K$ remains unchanged over time, it can be concluded that all heat supplied to the photosphere is converted into solar radiation energy.

But from the second law of thermodynamics it follows that there is a fundamental difference between electromagnetic (photon) energy and heat (kinetic energy of disordered motions of particles of matter), which manifests itself in the asymmetry of the direction of the processes of their mutual transformation into each other. This means that in a spontaneous process, electromagnetic energy can be completely converted into heat, while such a reverse process is impossible. Heat is never and nowhere completely converted into any other non-thermal energy. On the contrary, all known forms of energy, with the possible exception of gravitational energy, have a steady tendency to spontaneously and completely turn into thermal energy. Consequently, under no circumstances can the photosphere convert all the heat supplied to it into solar radiation, since in this case the Sun becomes a perpetual motion machine of the second kind, which is impossible. But then a completely non-trivial question arises: where does that part of the thermal energy that was supplied to the photosphere, but was not carried away into space by the photons of solar radiation, go?

It is easy to see that in a solar heat engine, of its three obligatory elements, only a heater and a working body are present, while a cooler is clearly not visible. Heat exchange between the photosphere and the external environment (chromosphere, corona) is impossible due to its extreme rarefaction and transparency for solar radiation, and there are no other bodies on the Sun that the photosphere could transfer heat to.

But in the absence of a cooler, the solar heat engine should not work at all. However, we know that it has been working for several billion years. On the other hand, we know that the failure of the second law of thermodynamics is as unlikely as the observation of a spontaneous transition of heat from a cold body to a hot one. Hence it follows that if we accept the second law of thermodynamics, then it is necessary to admit that the heat engine of the Sun is properly equipped, and it has a cooler, to which the working body gives off part of the heat of the heater. The problem is only in identifying the cooler or, figuratively speaking, in finding the "exhaust pipe" of the solar heat engine, which must certainly be in its photosphere.

Let us now pay attention to the fact that solar radiation is close to the equilibrium thermal radiation of a black body. This means that in the photosphere, radiation and matter have the same temperature, which, of course, increases with depth, but in such a way that in each elementary volume of the photosphere, the radiation temperature (average photon energy) and matter temperature (average thermal energy of particles) practically coincide. (It is believed that with a 1 km deepening into the photosphere, the temperature increases $\Delta T = 10\ K$.) In other words, the photosphere is in a state of local thermodynamic equilibrium and in general the principle of detailed equilibrium between the processes of absorption and emission of photons is fulfilled, with the exception, perhaps, a thin surface layer. Consequently, the photosphere for solar radiation is a conservative environment, and it would seem impossible to find any dissipative regions in it that play the role of a solar heat engine cooler.

However, not everything is so hopeless. Now is the time to remember about sunspots, but not about dark and cold sunspots, which the official physics of the Sun, raising their "coldness" to the rank of an unshakable postulate, is almost not interested. We are talking about the dark and hot sunspots, which they really are. In[1,2,3] the author has shown and confirmed in a model experiment that in sunspots, local thermodynamic equilibrium, therefore, the principle of detailed equilibrium, as well as Kirchhoff's law, are sharply violated, the culprit of which is their magnetic fields. In the umbra of a sunspot, the magnetic field almost completely suppresses (by means of magnetic-spin suppression) the processes of recombination of negative hydrogen ions, which are responsible for all visible radiation from the Sun, but does not interfere with the processes of their photoionization, which are responsible for the absorption of photons of the same visible solar radiation. This leads to the fact that the photospheric gas in sunspots, continuously heating up, turns into a high-temperature hydrogen-helium plasma with an admixture of ions of all other elements present in the photosphere. Since hydrogen-helium plasma at temperatures $T \leq 10^7 K$ is a source of mainly continuous bremsstrahlung electromagnetic radiation (free-free transitions of electrons), it is this radiation that is responsible for the bright glow of sunspots in the extreme ultraviolet and X-ray spectral ranges. The presence of this glow emanating from sunspots has been tacitly evidenced by numerous photographs of the Sun from the very beginning of the era of space heliophysical observations. («Tacitly» because the question of ultraviolet and X-ray radiation of sunspots in the literature is not only not discussed, but also not posed at all, since it goes beyond the prevailing paradigm of cold sunspots.)

Thus, it is easy to guess that the solar heat engine is cooled by its dark spots - relatively stable nonequilibrium dissipative structures that spontaneously arise in the equilibrium photosphere, thereby ensuring the viability of the Sun as a source of optical radiation. Without exaggeration, it can be argued that dark sunspots are as necessary for the dazzling radiance of the Sun as the solar core with a

thermonuclear stove built into it. Hence, it follows that sunspots must be precisely photospheric formations extending up to the convective zone, although their magnetic fields can extend much deeper. In addition, sunspots should always be present in the photosphere - both when we see them from the Earth's surface (large sunspots, groups of sunspots) and when we do not see them (many small spots). In this case, the total area of sunspots, or, metaphorically, the cross-sectional area of the "exhaust pipe" of the solar heat engine, should remain constant regardless of the phase of the solar activity cycle. It is these circumstances that can explain the amazing stability of the integral flux of visible solar radiation, the variations of which do not exceed±0.15%, as well as the fact that the area of all simultaneously observed sunspots never exceeds 0.5% of the solar disk area. Most likely, the recent images of the Sun in the extreme ultraviolet range of the spectrum obtained on June 15, 2020 by the Solar Orbiter / EUI Team probe (ESA & NASA) should be considered as confirmation of the above. These images are the first to record numerous bright spots covering the sun's disk, which have been called "solar campfires". In the author's opinion, these "campfires" are small sunspots, which, in the absence of large sunspots, play the role of an "exhaust pipe" of the solar heat engine.

In Figure 1 shows a diagram of a solar heat engine, on which the scale of some elements of the Sun is distorted, and the indicated numerical values of the quantities are chosen by the author taking into account the standard model of the Sun. In this diagram, Q_1 is the heat flow supplied by the heater to the working body, Q_2 is the heat flow given by the working body (photosphere) to the cooler with a temperature $T_2 = T_{spots}$ equal to the temperature of the sunspot matter, $U_{phot.}$ is the power of the solar heat engine, equal to the total solar radiation flow. The temperature of the heater $T_1 = 10^7 K$ is defined as the temperature of an isothermal spherical surface, the center of which coincides with the center of the Sun, and all regions of the release of thermonuclear energy in the Sun's core are inside it. Since the mass of the Sun is spherically symmetrically distributed over its volume, the temperature field and heat flow density, which are installed in the working body of the solar heat engine, also have spherical symmetry. In this regard, let us select two more isothermal spherical surfaces in the working body, the temperatures of which are known to us with greater or lesser accuracy. The first of them is the lower photospheric isotherm with temperature $T_{phot.1} = 10^4 K$, separating the convective zone and the photosphere itself, and the second is the upper photospheric isotherm with temperature $T_{phot.2} = 6000K$, which coincides with the surface of the Sun. Since in the spherical layer of the Sun, bounded by isotherms with temperatures $T_1 = 10^7 K$ and $T_{phot.1} = 10^4 K$, there are neither sources nor sinks of thermal energy, the magnitude of the heat flow Q_1 on the way between these isotherms should remain unchanged. This means that practically all the thermal energy Q_1 generated by the Sun's core per unit time, with the exception of relatively small losses for convection, turbulence and generation of solar magnetic fields, is supplied to the lower photospheric isotherm with temperature $T_{phot.1} = 10^4 K$.

Consider two possible modifications of a solar heat engine, differing in the choice of a heater and a working body. In the first modification, the heater is the core of the Sun with a temperature of $T_1 = 10^7 K$, the working body is the rest of the Sun, and the cooler is sunspots with a temperature of $T_2 = T_{spots}$. In the second modification, the heater is a spherical body with a surface temperature $T_{phot.1} = 10^4 K$, which includes the core, radiation and convective zones of the Sun, the working body is the photosphere, and the cooler is solar spots that receive heat Q_2 at a temperature $T_{phot.2} = 6000K$ of equilibrium radiation of the photosphere. Here we neglect the dependence of the radiation temperature on the depth of immersion in the photosphere and assume that $T_{phot.2} = 6000K$ is simultaneously the temperature of the photospheric gas, the radiation temperature and the temperature of the cooler.
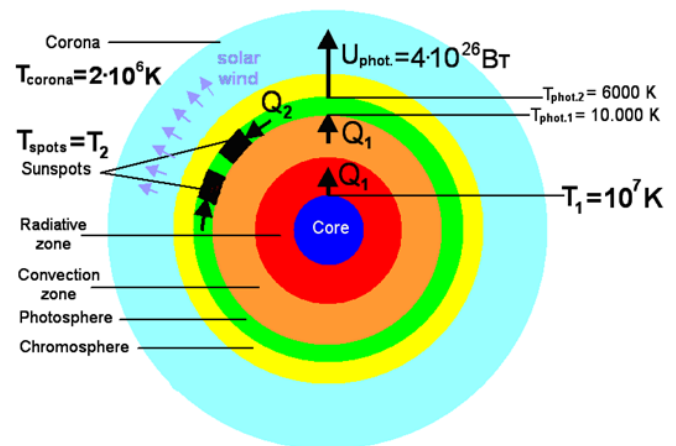

Figure 1 Diagram of the heat engine of the Sun.

The fact that in both modifications of the solar heat engine the temperature of the matter of sunspots heated by the radiation of the photosphere is approximately (as we will see below) by three orders of magnitude higher than the temperature of this radiation, should not confuse anyone. Something similar happens, for example, in thermonuclear research with radio-frequency heating of plasma in tokamaks or when targets are heated by laser radiation, as well as in a conventional microwave oven when heating food. Another thing is that the hot plasma of sunspots should have reliable thermal insulation from the photospheric gas, since only in this case, a temperature jump of several million degrees is possible at the border between them. The fact that such a temperature jump really exists is evidenced by almost all observational data, from the details of the evolution of the appearance of sunspots and ending with the brightness, spectrum and contrast of their glow against the background of the photosphere in ultraviolet and X-rays. However, it is difficult to give an adequate physical interpretation of this phenomenon, since all our knowledge about sunspots is obtained within the framework of the paradigm of cold sunspots, which was erroneous from the very beginning. Therefore, one can only guess about the properties of the plasma of hot sunspots and about its behavior in the magnetic fields of these spots. According to the author, the required degree of thermal insulation of the sunspot plasma from the photospheric gas can be provided by two permanent factors. The first factor is the vertical magnetic fields of sunspots, which significantly reduce the thermal conductivity of the plasma in the direction transverse to the magnetic field, especially if we take into account the rapid movement of this plasma along the magnetic field outward of the sunspots (the Evershed effect). The

second factor is a double electric layer on the surface of the plasma, capable of elastically reflecting hot electrons striving to leave the sunspot, which would drastically weaken the main electronic component of the thermal conductivity of the hot sunspot plasma. The mechanisms of the formation of electric double layers on the surface of a plasma or bodies adjacent to it can be considered known in most specific cases, but they can differ significantly depending on the properties of a given plasma and bodies in contact with it, as well as on the presence or absence of a magnetic field in the plasma. (Note that none of these factors interfere with the transit of photons through sunspots.

The functioning of the solar heat engine in its first modification is as follows. The heater transfers heat Q_1 to the working body at a temperature $T_1 = 10^7\,K$ per unit time, which in the photosphere is completely converted into the energy of equilibrium electromagnetic radiation. However, only part of this radiation $U_{phot.} = Q_1 - Q_2$, corresponding to the «useful work» of the solar heat engine, leaves the photosphere into space as solar radiation. The rest of the radiation energy, equal to $Q_2 = Q_1 - U_{phot.}$, is transferred to the cooler, i.e. sunspots with a temperature of $T_2 = T_{spots}$. The functioning of the solar heat engine in the second modification follows the same scheme, differing only in the values of the heater and cooler temperatures. It is clear that these modifications do not in any way affect the physical essence of the solar heat engine. They are considered in order to estimate the values of the unknown parameters of this heat engine - Q_1, Q_2 and T_{spots} for the known values of the parameters $U_{phot.} = 4{\cdot}10^{26}\,W$, $T_{phot.2} = 6000K$ and the selected values of the parameters $T_1 = 10^7\,K$, $T_{phot.1} = 10^4\,K$. The estimation method is based on the fact that the efficiency of the Carnot machine is uniquely determined by the temperatures of the heater and cooler.

If we assume that the temperature $T_{phot.1} = 10^4\,K$ is equal to the temperature of the lower isotherm of the photosphere, where matter and radiation are in thermal equilibrium with each other, and the temperature $T_1 = 10^7\,K$ is equal to the temperature of the Sun's core, then in the approximation of a reversible Carnot machine, the following equalities should be satisfied:

$$\varsigma_{Sun} = \frac{T_1 - T_{spots}}{T_1} = \frac{T_{phot.1} - T_{phot.2}}{T_{phot.1}} = \frac{Q_1 - Q_2}{Q_1} = \frac{U_{phot.}}{Q_1} \quad ., (3)$$

where ς_{Sun} is the efficiency of the solar heat engine. Since $\varsigma_{Sun} = (T_{phot.1} - T_{phot.2})/T_{phot.1} = 0.4$, then from expression (3) we find that $Q_1 = 10^{27}\,W$, $Q_2 = 6{\cdot}10^{26}\,W$, $T_{spots} = 6{\cdot}10^6\,K$.

From the obtained estimates of the values of the parameters of the solar heat engine, the most interesting is the temperature of the matter of sunspots $T_{spots} \sim {\cdot}6{\cdot}10^6\,K$, which play the role of a cooler of this heat engine. This means that in the solar photosphere throughout its depth, starting from the convective zone, there are many sources of thermal energy, the temperature of which is three orders of magnitude higher than the temperature of their environment, which is equivalent to the presence of heat engines constantly operating in the solar photosphere.

The heaters of these heat engines are separate sunspots, the working body is the convective zone gas entering the sunspots from below, and the photospheric gas on the Sun's surface, and the cooler is the Sun's atmosphere, represented by its corona with a temperature of $T_{corona} = 2{\cdot}10^6\,K$. Since the temperature of sunspots is the same, then in the Carnot approximation the efficiency of each of these heat engines scattered over the surface of the Sun is $\eta_{Sun\,2} = (T_{spots} - T_{corona})/T_{spots} = 0.67$, and their total power $P_{Sun-2} = \eta_{Sun\,2}{\cdot}Q_2 = 4{\cdot}10^{26}\,W$. (It should be noted that the total power of the heat engines of the photosphere coincides with the power of the main heat engine of the Sun.) Here it is appropriate to draw an analogy with terrestrial natural heat engines, which are well known to us by their actions (winds, storms, hurricanes, and the like). Their occurrence is due to the fact that various regions of the Earth's atmosphere and hydrosphere unevenly accumulate the energy of solar radiation, as a result of which temperature gradients are formed between them, which generate many different thermal machines of the Earth. And although the temperature differences between heaters and coolers in these heat engines are usually small, the results of their operation are often quite impressive. Something similar, only on an incomparably more grandiose scale, is taking place in the photosphere and in the atmosphere of the Sun.

Conclusion

Two heat engines of approximately the same power are constantly operating on the Sun. The first of them is the global heat engine of the Sun, which works due to the heat released in its core. The main result of the "useful work" of this heat engine is the solar radiation flow $U_{phot.} \sim 4{\cdot}10^{26}$ W. The second of them is the heat engine of the photosphere and the atmosphere of the Sun, which works due to the heat of dark hot sunspots, the substance of which is heated by the radiation of the photospheric gas. The main results of the "useful work" of this heat engine are the solar wind blowing from the umbra of sunspots, plus all other electromagnetic (light) and mechanical phenomena and processes occurring in the solar photosphere, the total power of which is $P_{Sun-2} \sim 4{\cdot}10^{26}$ W. The main conclusion that follows from all of the above can be formulated as follows. Matter, energy, and momentum (in any form) can enter the Sun's atmosphere only from its photosphere. Not a single phenomenon of solar activity can arise by itself in the chromosphere or in the corona of the Sun. The solar magnetic field is a necessary, active, regulating or directing factor in many phenomena of solar activity. But the ideas dominating in modern official heliophysics that solar magnetic fields are both the cause and the source of energy for all phenomena of solar activity have absolutely no physical substantiation, as well as any observational evidence.

Acknowledgments

Conflicts of interest

Author declares that there is no conflict of interest.

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