Axion mechanism of Sun luminosity and TSI variations:
light shining through the solar radiation zone

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Abstract

It is shown that the hypothesis of the axion mechanism of Sun luminosity suggesting that the solar axion-like particles are born in the core of the Sun and may be efficiently converted back into $\gamma$-quanta in the magnetic field of the solar overshoot tachocline is physically relevant. As a result, it is also shown that the intensity variations of the $\gamma$-quanta of axion origin, induced by the magnetic field variations in the tachocline, directly cause the Sun luminosity and total solar irradiance (TSI) variations and eventually characterize the active and quiet states of the Sun.

Within the framework of this mechanism estimations of the strength of the axion coupling to a photon ($g_{a\gamma} \approx 7.2 \cdot 10^{-11} \text{GeV}^{-1}$) and the axion-like particle mass ($m_a \sim 10^{-5} \text{eV}$) have been obtained. It is also shown that the claimed axion parameters do not contradict any known experimental and theoretical model-independent limitations.

1 Introduction

A hypothetical pseudoscalar particle called axion is predicted by the theory related to solving the CP-invariance violation problem in QCD. The most important parameter determining the axion properties is the energy scale $f_a$ of the so-called U(1) Peccei-Quinn symmetry violation. It determines both the axion mass and the strength of its coupling to fermions and gauge bosons including photons. However, in spite of the numerous direct experiments, they have not been discovered so far. Meanwhile, these experiments together with the astrophysical and cosmological limitations leave a rather narrow band for the permissible parameters of invisible axion (e.g., $10^{-6} \text{eV} < m_a < 10^{-3} \text{eV}$ [1]), which is also a well-motivated cold dark matter candidate in this mass region [1, 2].

A whole family of axion-like particles (ALP) with their own features may exist along with axions having the similar Lagrangian structure relative to the Peccei-Quinn axion, as well as their own distinctive features. It consists in the fact that if they exist, the connection between their mass and their constant of coupling to photons must be highly weakened, as opposed to the axions. It should also be mentioned that the phenomenon of photon-ALP mixing in the presence of the electromagnetic field not only leads to the classic neutrino-like photon-ALP oscillations, but also causes the change in the polarization state of the photons (the $a\gamma\gamma$ coupling acts like a
polarimeter [3]) propagating in the strong enough magnetic fields. It is generally assumed that there are light ALPs coupled only to two photons, although the realistic models of ALPs with couplings both to photons and to matter are not excluded [4]. Anyway, they may be considered a well-motivated cold dark matter candidate [1, 2] under certain conditions, just like axions.

It is interesting to note that the photon-ALP mixing in magnetic fields of different astrophysical objects including active galaxies, clusters of galaxies, intergalactic space and the Milky Way, may be the cause of the remarkable phenomena like dimming of stars luminosity (e.g. supernovae in the extragalactic magnetic field [5, 6]) and "light shining through a wall" (e.g., light from very distant objects, traveling through the Universe [3, 7]). In the former case the luminosity of an astrophysical object is dimmed because some part of photons transforms into axions in the object’s magnetic field. In the latter case photons produced by the object are initially converted into axions in the object’s magnetic field, and then after passing some distance (the width of the "wall") are converted back into photons in another magnetic field (e.g. in the Milky Way), thus emulating the process of effective free path growth for the photons in astrophysical medium [8, 9].

For the sake of simplicity let us hereinafter refer to all such particles as axions if not stated otherwise.

In the present paper we consider the possible existence of the axion mechanism of Sun luminosity 1 based on the "light shining through a wall" effect. To be more exact, we attempt to explain the axion mechanism of Sun luminosity by the "light shining through a wall", when the photons born mainly in the solar core are at first converted into axions via the Primakoff effect [11] in its magnetic field, and then are converted back into photons after passing the solar radiative zone and getting into the magnetic field of the overshoot tachocline. In addition to that we obtain the consistent estimates for the axion mass ($m_a$) and the axion coupling constants to photons ($g_{a\gamma}$), nucleons ($g_{an}$) and electrons ($g_{ae}$), basing on this mechanism, and verify their values against the axion model results and the known experiments including CAST, ADMX, RBF.

2 Photon-axion conversion and the case of maximal mixing

Let us give some implications and extractions from the photon-axion oscillations theory which describes the process of the photon conversion into an axion and back under the constant magnetic field $B$ of the length $L$. It is easy to show [7] that in the case of the negligible photon absorption coefficient ($\Gamma_\gamma \to 0$) and axions decay rate ($\Gamma_a \to 0$) the conversion probability is

$$P_{\gamma \leftrightarrow a} = (\Delta_{a\gamma} L)^2 \sin^2 \left( \frac{\Delta_{\text{osc}} L}{2} \right) / \left( \frac{\Delta_{\text{osc}} L}{2} \right)^2$$

(1)

where the oscillation wavenumber $\Delta_{\text{osc}}$ is given by

$$\Delta_{\text{osc}} = (\Delta_{pl} + \Delta_{Q,\perp} - \Delta_a)^2 - 4\Delta_{a\gamma}^2$$

(2)

while the mixing parameter $\Delta_{a\gamma}$, the axion-mass parameter $\Delta_a$, the refraction parameter $\Delta_{pl}$ and the QED dispersion parameter $\Delta_{Q,\perp}$ may be represented by the following expressions:

$$\Delta_{a\gamma} = \frac{g_{a\gamma} B}{2} = 540 \left( \frac{g_{a\gamma}}{10^{-14} \text{GeV}} \right) \left( \frac{B}{1 \text{G}} \right) \text{pc}^{-1}$$

(3)

$$\Delta_a = \frac{m^2}{2E_a} = 7.8 \cdot 10^{-11} \left( \frac{m_a}{10^7 \text{eV}} \right) \left( \frac{10^{19} \text{eV}}{E_a} \right) \text{pc}^{-1}$$

(4)

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1Let us point out that the axion mechanism of Sun luminosity used for estimating the axion mass was described for the first time in 1978 in the paper [10].
Here, $g_{a\gamma}$ is the constant of axion coupling to photons; $B$ is the transverse magnetic field; $m_a$ and $E_a$ are the axion mass and energy; $\omega_{pl}^2 = 4\pi\alpha n_e/m_e$ is an effective photon mass in terms of the plasma frequency if the process does not take place in vacuum, $n_e$ is the electron density, $\alpha$ is the fine-structure constant, $m_e$ is the electron mass; $\Delta_{Q,\perp}$ is the effective mass square of the transverse photon which arises due to interaction with the external magnetic field.

The conversion probability (1) is energy-independent, when $2\Delta_{a\gamma} \gg |\Delta_{osc}|$, i.e.

$$ P_{\gamma\leftrightarrow a} \simeq \sin^2 (\Delta_{a\gamma}L), $$

(7)

or, whenever the oscillatory term in (1) is small ($\Delta_{osc} L / 2 \to 0$), implying the limiting coherent behavior

$$ P_{\gamma\leftrightarrow a} \simeq \left( \frac{g_{a\gamma}BL}{2} \right)^2. $$

(8)

As it is shown in [7], in the energy-independent case (7), when the following inequalities are satisfied:

$$ \Delta_{a\gamma} \gg \Delta_{Q,\perp}, \quad 2\Delta_{a\gamma} \gg \Delta_a, \quad 2\Delta_{a\gamma} \gg \Delta_{pl}, $$

(9)

it is easy to derive the following relations by means of (3)-(6):

$$ \left( \frac{B}{1G} \right) \left( \frac{E_a}{10^{19}eV} \right) \ll 7.52 \cdot 10^{-9}, $$

(10)

$$ E_a \gg 70eV \left( \frac{m_a}{10^{-9}eV} \right)^2 \left( \frac{B}{1G} \right)^{-1} \left( \frac{10^{-10}GeV^{-1}}{g_{a\gamma}} \right), $$

(11)

$$ n_e \ll 10^{20}cm^{-3} \left( \frac{E_a}{10^{19}eV} \right) \left( \frac{B}{1G} \right). $$

(12)

The condition of maximum mixing (i.e. $P_{\gamma\leftrightarrow a} \to 1$ in (7)) is obviously provided by the size $L$ of the region that satisfies the conditions (10)-(12) together with the following expression:

$$ L \sim \frac{\pi}{\Delta_{osc}} = 2.9 \cdot 10^{-3} \text{pc} \left( \frac{B}{1G} \right)^{-1} \left( \frac{10^{-10}GeV^{-1}}{g_{a\gamma}} \right), $$

(13)

taking into account that $\Delta_{osc} \approx 2\Delta_{a\gamma}$.

From now on we are going to be interested in the energy-independent case (7) and the relations (10)-(13) which play the key role in determination of the axion mechanism of Sun luminosity hypothesis parameters (the axion coupling constant to photons $g_{a\gamma}$, the transverse magnetic field $B$ of length $L$ and the axion mass $m_a$).

### 3 Axion mechanism of Sun luminosity

Our hypothesis is that the solar axions which are born in the solar core [1, 2] through the known Primakoff effect [11], may be converted back into $\gamma$-quanta in the magnetic field of the solar tachocline (the base of the solar convective zone). The magnetic field variations in the tachocline cause the converted $\gamma$-quanta intensity variations in this case, which in their turn cause the variations of the Sun luminosity known as the active and quiet Sun states. Let us consider this phenomenon in more detail below.

As we noted above, the expression (1) for the probability of the axion-photon oscillations in the transversal magnetic field was obtained for the media with the quasi-zero refraction, i.e. for
the media with a negligible photon absorption coefficient \( \Gamma_\gamma \to 0 \). It means that in order for
the axion-photon oscillations to take place without any significant losses, a medium with a very
low or quasi-zero density is required, which would suppress the processes of photon absorption
almost entirely.

Surprisingly enough, it turns out that such ”transparent” media can take place, and not
only in plasmas in general, but straight in the convective zone of the Sun. Here we generally
mean the so-called magnetic flux tubes, the properties of which are examined below.

3.1 Channeling of \( \gamma \)-quanta along the magnetic flux tubes (waveguides) in the Sun convective zone

The idea of the energy flow channeling along a fanning magnetic field has been suggested for the
first time by Hoyle [12] as an explanation for darkness of umbra of sunspots. It was incorporated
in a simple sunspot model by Chitre [13]. Zwaan [14] extended this suggestion to smaller flux
tubes to explain the dark pores and the bright faculae as well. Summarizing the research of the
convective zone magnetic fields in the form of the isolated flux tubes, Spruit and Roberts [15]
suggested a simple mathematical model for the behavior of thin magnetic flux tubes, dealing
with the nature of the solar cycle, sunspot structure, the origin of spicules and the source of
mechanical heating in the solar atmosphere. In this model, the so-called thin tube approximation
is used (see [15] and references therein), i.e. the field is conceived to exist in the form of slender
bundles of field lines (flux tubes) embedded in a field-free fluid (Fig.1). Mechanical equilibrium
between the tube and its surrounding is ensured by a reduction of the gas pressure inside the
tube, which compensates the force exerted by the magnetic field. In our opinion, this is exactly
the kind of mechanism Parker [16] was thinking about when he wrote about the problem of flux
emergence: ”Once the field has been amplified by the dynamo, it needs to be released into the
convection zone by some mechanism, where it can be transported to the surface by magnetic
buoyancy” [17].

In order to understand magnetic buoyancy, let us consider an isolated horizontal flux tube
in pressure equilibrium with its non-magnetic surroundings (Fig.1). The magnetic field \( \vec{B} \)
alternating along the vertical axis \( z \) induces the vortex electric field in the magnetic flux tube
containing dense plasma. The charged particles rotation in plasma with the angular velocity \( \omega \)
leads to a centrifugal force per unit volume

\[
|\vec{F}| \sim \rho |\vec{\omega}|^2 r. 
\]  

If we consider this problem in a rotating noninertial reference frame, such noninertiality,
according to the equivalence principle, is equivalent to ”introducing” a radial non-uniform grav-
itational field with the ”free fall acceleration”

\[
g(r) = |\vec{\omega}|^2 r. 
\]  

In such case the pressure difference inside \( (p_{int}) \) and outside \( (p_{ext}) \) the rotating ”liquid”
of the tube may be treated by analogy with the regular hydrostatic pressure (Fig.2).

Let us pick a radial ”liquid column” inside the tube as it is shown in Fig.2. Since the ”gravity”
is non-uniform in this column, it is equivalent to a uniform field with ”free fall acceleration”

\[
\langle g(r) \rangle = \frac{1}{2} |\vec{\omega}|^2 R, 
\]  

where \( R \) is the tube radius which plays a role of the ”liquid column height” in our analogy.

By equating the forces acting on the chosen column similar to hydrostatic pressure (Fig.2),
we derive:

\[
p_{ext} = p_{int} + \frac{1}{2} \rho |\vec{\omega}|^2 R^2. 
\]
This raises the question as to what physics is hidden behind the "centrifugal" pressure. In this relation, let us consider the magnetic field energy density

\[ w_B = \frac{|\mathbf{B}|^2}{2\mu_0}, \]  

(18)

where \( \mu_0 \) is the magnetic permeability of vacuum.

Suppose that the total magnetic field energy of the "growing" tube grows linearly between the tachocline and the photosphere. In this case if the average total energy of the magnetic field in the tube transforms into the kinetic energy of the tube matter rotation completely, it is easy to show that

\[ \langle E_B \rangle = \frac{1}{2} w_B V = \frac{1}{2} \frac{|\mathbf{B}|^2}{2\mu_0} V = \frac{I|\mathbf{\omega}|^2}{2}, \]  

(19)
Figure 2: Representation of a "hydrostatic equilibrium" in the rotating "liquid" of a magnetic flux tube.

where \( I = mR^2/2 \) is the tube's moment of inertia about the rotation axis, \( m \) and \( V \) are the mass and the volume of the tube medium respectively.

From (19) it follows that

\[
\frac{\rho |\vec{\omega}|^2 R^2}{2} = \frac{|\vec{B}|^2}{2\mu_0}.
\]

Finally, substituting (20) into (17) we obtain the desired relation

\[
p_{\text{ext}} = p_{\text{int}} + \frac{|\vec{B}|^2}{2\mu_0},
\]

which is exactly equal to the well-known expression by Parker [22], describing the so-called self-confinement of force-free magnetic fields.

In spite of the obvious, though turned out to be surmountable, difficulties of the expression (14) application to the real problems, it was shown (see [15] and Refs. therein) that strong buoyancy forces act in magnetic flux tubes of the required field strength \( (10^4 - 10^5 \text{ G}) [23] \). Under their influence tubes either float to the surface as a whole (e.g., Fig.1 in [24]) or they form loops of which the tops break through the surface (e.g. Fig.1 in [14]) and lower parts descend to the bottom of the convective zone, i.e. to the overshoot tachocline zone. The convective zone, being unstable, enhanced this process [25, 26]. Small tubes take longer to erupt through the surface because they feel stronger drag forces. It is interesting to note here that the phenomenon of the drag force which raises the magnetic flux tubes to the convective surface with the speeds about 0.3-0.6 km/s, was discovered in direct experiments using the method of time-distance helioseismology [19]. Detailed calculations of the process [27] show that even a tube with the size of a very small spot, if located within the convective zone, will erupt in less than two years. Yet, according to [27], horizontal fields are needed in overshoot tachocline zone, which survive for about 11 yr, in order to produce an activity cycle.

In other words, a simplified scenario of magnetic flux tubes (MFT) birth and space-time evolution (Fig.1a) may be presented as follows. MFT is born in the overshoot tachocline zone (Fig.1c) and rises up to the convective zone surface (Fig.1b) without separation from the tachocline (the anchoring effect), where it forms the sunspot (Fig.1d) or other kinds of active solar regions when intersecting the photosphere. There are more fine details of MFT physics expounded in overviews by Hassan [17] and Fisher [24], where certain fundamental questions, which need to be addressed to understand the basic nature of magnetic activity, are discussed in detail: How is the magnetic field generated, maintained and dispersed? What are its proper-
ties such as structure, strength, geometry? What are the dynamical processes associated with magnetic fields? What role do magnetic fields play in energy transport?

Dwelling on the last extremely important question associated with the energy transport, let us note that it is known that thin magnetic flux tubes can support longitudinal (also called sausage), transverse (also called kink), torsional (also called torsional Alfvén), and fluting modes (e.g. [28–32]); for the tube modes supported by wide magnetic flux tubes, see Roberts and Ulmschneider [31]. Focusing on the longitudinal tube waves known to be an important heating agent of solar magnetic regions, it is necessary to mention the recent papers by Fawzy [33], which showed that the longitudinal flux tube waves are identified as insufficient to heat the solar transition region and corona in agreement with previous studies [34].

In other words, the problem of generation and transport of energy by magnetic flux tubes remains unsolved in spite of its key role in physics of various types of solar active regions.

Interestingly, this problem may be solved in a natural way in the framework of the "axion" model of the Sun. It may be shown that the inner pressure, temperature and matter density decrease rapidly in a magnetic tube "growing" between the tachocline and the photosphere. This fact is very important, since the rapid decrease of these parameters predetermines the decrease of the medium opacity inside the magnetic tube, and, consequently, increases the photon free path inside the magnetic tube drastically. In other words, such decrease of the pressure, temperature and density inside the "growing" magnetic flux tube is a necessary condition for the virtually ideal (i.e. without absorption) photon channeling along such magnetic tube. The latter specifies the axion-photon oscillations efficiency inside the practically empty magnetic flux tubes.

### 3.2 Hydrostatic equilibrium and a sharp tube medium cooling effect

Let us assume that the tube has the length \( l(t) \) by the time \( t \). Then its volume is equal to \( S \cdot l(t) \) and the heat capacity is

\[
c \cdot \rho \cdot S l(t),
\]

where \( S \) is the tube cross-section, \( \rho(t) \) is the density inside the tube, \( c \) is the specific heat capacity.

If the tube becomes longer by \( v(t) dt \) for the time \( dt \), then the magnetic field energy increases by

\[
\frac{1}{2} \frac{|\vec{B}|^2}{2 \mu_0} S \cdot v(t) dt,
\]

where \( v(t) \) is the tube propagation speed.

The matter inside the tube, obviously, has to cool by the temperature \( dT \) so that the internal energy release maintained the magnetic energy growth. Therefore, the following equality must hold:

\[
c \rho(t) l(t) \frac{dT}{dt} S = -\frac{1}{2} \frac{|\vec{B}|^2}{2 \mu_0} S \cdot v(t)
\]

Taking into account the fact that the tube grows practically linearly [19] i.e. \( vt = l \), Parker relation (21) and the tube’s equation of state

\[
p_{int}(t) = \frac{\rho}{\mu_\ast} R_\ast T(t) \iff \rho = \frac{\mu_\ast}{R_\ast} \frac{p_{int}}{T(t)},
\]

the equality (24) may be rewritten (by separation of variables) as follows:

\[
\frac{dT}{T} = -\frac{R_\ast}{2c \mu_\ast} \left[ \frac{p_{ext}}{p_{int(t)}} - 1 \right] \frac{dt}{t},
\]

where \( \mu_\ast \) is the tube matter molar mass, \( R_\ast \) is the universal gas constant.
After integration of (26) we obtain

$$\ln \left[ \frac{T(t)}{T(0)} \right] = -R_\ast \int_0^t \left[ \frac{p_{ext}}{p_{int}(\tau)} - 1 \right] \frac{d\tau}{\tau}. \quad (27)$$

It is easy to see that the multiplier $(1/\tau)$ in (27) assigns the region near $\tau = 0$ in the integral. The integral converges, since

$$\lim_{\tau \to 0} \left[ \frac{p_{ext}}{p_{int}(\tau)} - 1 \right] = 0. \quad (28)$$

Expanding $p_{int}$ into Taylor series and taking into account that $p_{int}(\tau = 0) = p_{ext}$, we obtain

$$p_{int}(\tau) = p_{ext} + \frac{dp_{int}(\tau = 0)}{d\tau} = p_{ext}(1 - \gamma \tau), \quad (29)$$

where

$$\gamma = -\frac{1}{p_{ext}} \frac{dp_{int}(\tau = 0)}{d\tau} = -\frac{1}{p_{int}(\tau = 0)} \frac{dp_{int}(\tau = 0)}{d\tau}. \quad (30)$$

From (29) it follows that

$$\frac{p_{ext}}{p_{int}(\tau)} - 1 = \frac{1}{1 - \gamma \tau} - 1 \approx \gamma \tau, \quad (31)$$

therefore, substituting (31) into (27), we find its solution in the form

$$T(t) = T(0) \exp \left( -\frac{R_\ast}{2c_\mu_*} \gamma t \right). \quad (32)$$

It is extremely important to note here that the solution (32) points at the remarkable fact that at least at the initial stages of the tube formation its temperature decreases exponentially, i.e. very sharply. The same conclusion can be made for the pressure and the matter density in the tube. Let us show it.

Assuming that relation (30) holds not only for $\tau = 0$, but also for small $\tau$ close to zero, we obtain

$$p_{int}(t) = p_{int}(0) \exp(-\gamma t), \quad (33)$$

i.e. the inner pressure also decreases exponentially, but with the different exponential factor.

Further, assuming that the heat capacity of a molecule in the tube is

$$c = \frac{i R_\ast}{2 \mu_*}, \quad (34)$$

where $i$ is a number of molecule’s degrees of freedom, and substituting the expressions (32) and (33) into the tube’s equation of state, we derive the expression for the matter density in the tube

$$\rho(t) = \frac{\mu_* p_{int}(0)}{R_\ast T(0)} \exp \left[ -\left( 1 - \frac{1}{i} \right) \gamma t \right]. \quad (35)$$

Taking into account that $i \geq 3$, we can see that the density decreases exponentially just like the temperature (32) and the pressure (33).

### 3.3 Ideal photon channeling (without absorption) conditions inside the magnetic flux tubes

Let us calculate the inner pressure $p_{int}$ of the magnetic flux tube in the solar tachocline. In the framework of the standard model of the Sun the pressure in the tachocline zone is about $\sim 6 \times 10^{12} \ Pa$, while the magnetic field strength reaches 400 T, according to our estimates (Fig.3).
Figure 3: (a) Growth rates for magnetic shear instabilities are plotted as functions of the initial latitude (vertical axes) and the field strength (horizontal axes) of a toroidal band. Shaded areas indicate instability in 0.1-100T band (gray) and 200-400T band (green). Contour lines represent \( m = 1 \) and \( m = 2 \) symmetric (S) and antisymmetric (A) modes as indicated. The non-dimensional model is normalized in such a way that the growth rate of 0.01 corresponds to an e-folding growth time of 1 year. The parameter \( s \) is the fractional angular velocity contrast between equator and pole and the reduced gravity \( G \) (adopted from [35]). In addition, a hidden part of the "latitude magnetic field in overshoot tachocline zone" dependence, which was missing on the original plot (Fig.11 in [35]), is plotted to the right of the dashed line. (b) Solar images at photon energies from 250 eV up to a few keV from the Japanese X-ray telescope Yohkoh (1991-2001) (adopted from [36]). The following shows solar X-ray activity during the last maximum of the 11-year solar cycle.

Then from the hydrostatic condition by Parker (21) it follows that the inner pressure of the magnetic flux tube in the solar tachocline is equal to

\[
p_{\text{int}} \sim 6 \cdot 10^{12} - 4 \cdot 10^{10} \approx 6 \cdot 10^{12} \ \text{[Pa]},
\]

which is comparable to the external pressure.

However, the situation changes drastically within the framework of the "axion" model of the Sun. Since the overshoot tachocline zone is located substantially higher than the base of the convective zone (see Fig.4 and the corresponding text) in the "axion" model, let us suppose that the plasma pressure outside the magnetic tube near the new overshoot tachocline zone location falls by an order of magnitude and is about \( \sim 10^{11} \ \text{Pa} \). In such case it is easy to see that the magnetic field \( \sim 500 \ \text{T} \) compensates the outer pressure almost completely, and the inner pressure

\[
p_{\text{int}} \sim 10^{11} - O(10^{11}) \to 0 \ \text{[Pa]}
\]

becomes ultralow.

The result (37) means that according to (33), the temperature and the matter density decrease together with the inner pressure, and the decrease is sharply exponential, because the exponential factor in (31) becomes very large

\[
\gamma \tau = \frac{p_{\text{ext}}}{p_{\text{int}}(\tau)} - 1 \to \infty.
\]

Because of the fact that the density, pressure and temperature in the tube are ultralow, they virtually do not influence the radiation transport in these tubes at all. In other words, the Rosseland free paths for \( \gamma \)-quanta inside the tubes are so big that the Rosseland opacity [37–44] and the absorption coefficients (\( \Gamma_{\gamma} \to 0 \)) tend to zero. The low refractivity (or high transparency) is achieved for the following limiting condition:

\[
p_{\text{ext}} \approx \frac{\left| \vec{B} \right|^2}{2\mu_0}.
\]

9
The obtained results should not be considered as a proof, but rather as some trial estimates that validate the substantiation of an almost ideal photon channeling mechanism along the magnetic flux tubes.

Although currently there is no deep and detailed understanding of the magnetic tubes formation processes in the tachocline, the following scenario may be supposed in the framework of the axion mechanism of solar luminosity. At the first stage this process is determined by the numerous magnetic tubes appearance (Fig. 4a) as a consequence of the shear flow instability development in the tachocline. As is shown above (e.g. (33)), the pressure inside these tubes
becomes ultralow causing the formation and rise of the magnetic steps in the tubes (Fig.4b). To put it differently, a kind of the magnetic capillary effect is observed in this case. A complete picture of the magnetic tube’s space-time evolution in the convective zone shown in Fig.4 is an illustration of the axion to $\gamma$-quanta conversion process (in the overshoot tachocline) with the formation of an active solar region in the photosphere (Fig.4c). It thereby reveals the nature of the unique energy transport mechanism through the convective zone by magnetic flux tubes.

3.4 Estimation of the axion-photon oscillation parameters

Let us consider the modulation of an axion flux emerging from the Sun core on passing through the solar tachocline region (ST) located beneath the base of the solar convective zone (Fig.4b). It is known that the thickness $\Delta_{ST}$ of ST obtained by Charbonneau et al. [45] is $\Delta_{ST}/R_S = 0.039 \pm 0.013$ at the equator and $\Delta_{ST}/R_S = 0.042 \pm 0.013$ at a latitude of 60°, suggesting that the tachocline may get somewhat wider at high latitudes but that the result is not statistically significant.

Taking into account that the value of the magnetic field strength $B_{OT}$ in the overshoot tachocline is $\sim 400$ T (see Fig.3) and setting the overshoot tachocline thickness $L_{OT}$ approximately equal $\sim 3 \cdot 10^4$ km (see Fig.4b) it is not hard to use the expression (13) in the form

$$\left(\frac{9 \cdot 10^{10}}{L_{OT}} \text{ km} \right) \left( \frac{1 \text{ G}}{B_{OT}} \right) \left( \frac{10^{-10} \text{ GeV}^{-1}}{g_{a\gamma}} \right) \sim 1$$

(40)

for estimating the axion coupling constant to photons

$$g_{a\gamma} \sim 7.2 \cdot 10^{-11} \text{ GeV}^{-1}.$$  

(41)

And finally let us give the estimates for the allowed axion masses which may be obtained on the basis of the linear limitations (10) and (11) with account of (41). The analysis of the upper linear limitations (Eq.(10)) and the lower ones (Eq.(11)) shows that the axion masses $3.5 \cdot 10^{-6}$ eV, $10^{-5}$ eV and $1.7 \cdot 10^{-5}$ eV are in good agreement with these limits (see Fig.5b). On the other hand, these mass values are obviously in a good agreement with the known experimental limitations shown in Fig.5a in the $m_a - g_{a\gamma}$ plane.

Thus, it is shown that the hypothesis about the possibility for the solar axions born in the core of the Sun to be efficiently converted back into $\gamma$-quanta in the magnetic field of the solar overshoot tachocline is relevant. Here the variations of the magnetic field in the solar tachocline are the direct cause of the converted $\gamma$-quanta intensity variations. The latter in their turn may be the cause of the overall solar luminosity variations known as the active and quiet Sun phases.

4 Axion mechanism of TSI variations

It is known [55, 56] that during the transition from the minimum to the maximum of the 11-year magnetic solar cycle, i.e. from the quiet to the active phase of the Sun, the relative TSI variations ($\Delta TSI$) are

$$\frac{|\Delta TSI|}{TSI} \sim 5 \cdot 10^{-4}.$$  

(42)

As the theoretical calculations show [56], such effect of solar activity modulation is associated with the magnetic energy release from the dynamo region to the photosphere and higher with the consequent transformation into radiation. According to [56], the surface (over-photosphere) magnetic fields are considered as the additional channels for energy transport from the inner layers of the Sun outwards in this case. Interestingly, such mechanism of Sun modulation is corroborated by the results of the papers [57–59], which conclude that the luminosity growth during the solar cycle maximum may be associated with the effective over-photosphere magnetic fields influence on the electromagnetic radiation output.
Figure 5: (a) Summary of astrophysical, cosmological and laboratory constraints on axions and axion-like particles. The exclusion regions labelled "Cosmology", "CAST (Phase-I)" and "SN 1987A" arise from experiments and astrophysical observations that do not require axion-like particle dark matter (for a review, see [46]). The lines labelled KSVZ [47, 48], DFSZ [49] and Arhion model [50, 51], show the theoretical prediction for the QCD axion. Green bands labelled ADMX [52] and RBF [53], show the experimentally excluded regions. The regions where they could form DM are displayed in different shades of red (for details in [54]). The yellow stars in the inset mark the permitted values for the axion-like-particles in the $m_a - g_{a\gamma}$ plane.

(b) The conditions (10) and (11) on the parameter plane "photon energymagnetic field" in various astrophysical objects (intergalactic space (IG), the Milky Way (MW), narrow- and broad-line regions in active galactic nuclei (NLR and BLR), gamma-ray bursts (GRB)). To facilitate comparisons, we adopt many of the conventions used by Fairbairn et al. [7]. The condition (11) is satisfied above red lines. Horizontal lines indicate typical values of $B$ for various astrophysical sources, the condition (10) is satisfied below a thick dashed green line: the mixing is possible below the green line but above the red lines as indicated, for $m_a = 3.5 \cdot 10^{-6} \text{eV}$, by the thick blue parts of the horizontal lines (for $g_{a\gamma} = 7.2 \cdot 10^{-11} \text{GeV}^{-1}$).

On the other hand, it is easy to show that the part of the axion luminosity $L_a$ in the total luminosity of the Sun $L_{\text{Sun}}$ with respect to (41) is [60]

$$\frac{L_a}{L_{\text{Sun}}} = 1.85 \cdot 10^{-3} \left(\frac{g_{a\gamma}}{10^{-10} \text{GeV}^{-1}}\right)^2 \sim 10^{-3}. \quad (43)$$

It should be mentioned that the comparison of the estimates (42) and (43) shows that the portion of the axions that are converted into $\gamma$-quanta does not exceed 50% which is highly important for the solar axion flux estimations performed in the real ground-based experiments. At the same time, despite the coincidence of the relative variations (42) and (43) by the order of magnitude, one should also keep in mind that the axion mechanism of Sun luminosity variations is somewhat different by the nature of its source, although it is also associated with the radiant energy input to the photosphere. As opposed to the classic mechanism of the Sun modulation mentioned above, the axion mechanism is determined by the magnetic tubes rising to the photosphere, and not by the over-photosphere magnetic fields. In this case the solar luminosity modulation is determined by the axion-photon oscillations in the magnetic field of the overshoot tachocline causing the formation and channeling of the $\gamma$-quanta inside the almost empty magnetic tubes (see Fig.4b). When the magnetic tubes cross the photosphere, they "open" (Fig.4c), and the $\gamma$-quanta are ejected to the photosphere, where their comfortable journey along the magnetic tubes (without absorption and scattering) ends. As the calculations by Zioutas et al. [36] show, the further destiny of the $\gamma$-quanta in the photosphere may be
Figure 6: (a) Reconstructed solar photon spectrum below 10 keV from the active Sun (red line) and quiet Sun (blue line) from accumulated observations (spectral bin is 6.1 eV wide). Adopted from [61]; (b) Axion mechanism of TSI variations: the soft part of the solar photon spectrum is invariant, and thus does not depend on the phase of the Sun (violet band), while the red and blue curves characterize the TSI increment in the active and quiet phases; (c) reconstructed solar photon spectrum fit in the active phase of the Sun by the quasi-invariant soft part of the solar photon spectrum and three spectra (44) degraded to the Compton scattering for column densities above the initial conversion place of 64, 16 (adopted from [36]) and 2 g/cm² (present paper). (d) The similar curves for the quiet phase of the Sun.

described by the Compton scattering, which actually agrees with the observed solar spectral shape (Fig.6c,d).

From the axion mechanism point of view it means that the solar spectra during the active and quiet phases (i.e. during the maximum and minimum solar activity) differ from each other by the smaller or larger part of the Compton spectrum only, the latter being produced by the γ-quanta of the axion origin ejected from the magnetic tubes into the photosphere.

A natural question arises at this point: "What are the real parts of the Compton spectrum of the axion origin in the active and quiet phases of the Sun respectively, and do they agree with the experiment?" Let us perform the mentioned estimations basing on the known experimental results by ROSAT/PSPC, where the Sun’s coronal X-ray spectra and the total luminosity during the minimum and maximum of the solar coronal activity were obtained [61].

With this in mind, let us suppose that the part of the differential solar axion flux at the Earth [60]

\[
\frac{d\Phi_a}{dE} = 6.02 \cdot 10^{10} \left( \frac{g_a \gamma}{10^{10} GeV^{-1}} \right)^2 E^{-2.481} \cdot \exp \left( -\frac{E}{1.205} \right) \ cm^{-2} s^{-1} keV^{-1},
\]

(44)
which characterizes the differential $\gamma$-spectrum of the axion origin $d\Phi_\gamma/dE$ and depends on the ratio of the total magnetic flux tubes cross-sectional area to the whole tachocline area, equal to 1/3, i.e.

$$\frac{d\Phi_\gamma}{dE} \approx \frac{1}{3} P_{a+\gamma} \frac{d\Phi_a}{dE} \text{photon} \cdot \text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1} \approx 2 \cdot 10^{-3} \frac{d\Phi_a}{dE} \text{ph} \cdot \text{cm}^{-2} \text{s}^{-1} \text{bin}^{-1},$$

(45)

where $P_{a+\gamma} = 1$ and the spectral bin is 6.1 eV wide (see Fig.6).

Fig.6c,d shows three differential Compton spectra (45) degraded for column densities above the initial conversion place of 64, 16 and 2 $g/cm^2$.

Apparently, the solar photon spectrum below 10 keV of the active Sun (the red curve in Fig.6a) reconstructed from the accumulated ROSAT/PSPC observations may be described by three Compton spectra for different column densities rather well (Fig.6c).

Similarly a reconstructed solar photon spectrum below 10 keV from the quiet Sun may be described (the blue curve in Fig.6a).

The analysis of the reconstructed solar photon spectra from the active and quiet Sun, which are consistent with the sum of the simulated Compton spectra, gives grounds for the assumption that the soft part of the solar photon spectrum does not depend on the phase of the Sun (the brown band in Fig.6b). Then the total Sun luminosity change during the solar cycle may be characterized by the total coronal luminosity variations:

$$\Delta L_{\text{Sun}} \approx \Delta L_{\text{corona}}$$

(46)

At the same time, according to [61], the Sun’s coronal X-ray luminosity measured in the ROSAT/PSPC experiments (Fig.6) is $(L^X_{\text{corona}})_{\text{min}} \approx 2.7 \cdot 10^{26} \text{erg/s}$ at minimum and $(L^X_{\text{corona}})_{\text{max}} \approx 4.7 \cdot 10^{27} \text{erg/s}$ at maximum.

It may be shown (see Appendix A) that

$$\frac{\Delta L_{\text{Sun}}}{L_{\text{Sun}}} \approx \frac{\Delta L_{\text{corona}}}{L_{\text{Sun}}} \approx \frac{10^3 \Delta L^X_{\text{corona}}}{L_{\text{Sun}}} \approx 10^{-3}$$

(47)

where $L_{\text{Sun}} = 3.8418 \cdot 10^{33} \text{erg/s}$ is the solar luminosity [62].

The estimate (47) is in good agreement with both the theoretical axion impact estimate (43) and the observed TSI variations (42).

Thus it is shown that the axion mechanism of the TSI variations is physically relevant\(^2\). Within such mechanism the variations of the magnetic field in the solar tachocline are the direct cause of the converted $\gamma$-quanta intensity variations. The latter in their turn may be a reason of the total solar luminosity variations known as the active and quiet Sun states.

5 Axion mechanism of the solar Equator – Poles effects

The axion mechanism of Sun luminosity is largely validated by the experimental X-ray images of the Sun in the quiet (Fig.7a) and active (Fig.7b) phases [36] which clearly reveal the so-called Solar Equator – Poles effect (Fig.7b).

\(^2\)Let us remind the nontrivial fact that, strange as it may seem, the TSI variations are not the modulator of the global temperature in the Earth climatic system (ECS), since the TSI variations and the global temperature manifest the strong inverse correlation with 22-year lag (see Fig.1 in [63] or [64]). And vice versa, the (non-convertible) solar axion flux and the global temperature variations show the strong positive correlation with the same time lag. This fact plays the key role in the new theory of the Global Climate [63–66] explaining the mechanism of the axions’ impact on the Earth global climate. This is a very important aspect, because a large number of the modern climatologists still think that it is the TSI variations that are responsible for the Earth global temperature variations, obstinately ignoring the extremely small contribution of the TSI variations into the energy balance in the Earth atmosphere as well as the obvious experimental fact of the inverse (negative) correlation between the TSI and the Earth global temperature (see [63]). However, this problem requires a special discussion and will be considered in a separate paper.
Figure 7: **Top:** Solar images at photon energies from 250 eV up to a few keV from the Japanese X-ray telescope Yohkoh (1991-2001) (adopted from [36]). The following is shown: (a) a composite of 49 of the quietest solar periods during the solar minimum in 1996; (b) solar X-ray activity during the last maximum of the 11-year solar cycle. Most of the X-ray solar activity (right) occurs at a wide bandwidth of ±45° in latitude, being homogeneous in longitude. Note that ~95% of the solar magnetic activity covers this bandwidth.

**Bottom:** (c) Axion mechanism of TSI variations with the soft part of the solar photon spectrum independent of the Sun’s phases (brown band) and the red and blue curves characterizing the TSI increment in the active and quiet phases of the Sun, respectively; (d) Schematic picture of the radial traveling of the axions inside the Sun. Blue lines on the Sun designate the magnetic field. In the tachocline axions are converted into γ-quanta, that move towards the poles (blue cones) which form the experimentally observed Solar photon spectrum after passing the photosphere (Fig.6). Solar axions in the equatorial plane (blue bandwidth) are not converted by Primakoff effect, inset: diagram of the inverse coherent process). The variations of the solar axions may be observed at the Earth by special detectors like the new generation CAST-helioscopes [67].

The essence of this effect lies in the following. It is known that the axions may be transformed into γ-quanta by inverse Primakoff effect in the transverse magnetic field only. Therefore the axions that pass towards the poles (blue cones in Fig.7b) and equator (the blue band in Fig.7b) are not transformed into γ-quanta by inverse Primakoff effect, since the magnetic field vector is almost collinear to the axions’ momentum vector. The observed nontrivial X-ray distribution in the active phase of the Sun may be easily and naturally described within the framework of the axion mechanism of Sun luminosity or TSI.

After the axions transformation into photons in the tachocline, these photons travel through the entire convective zone along the magnetic flux tubes, as described in Section 3.1, up to
the photosphere. In the photosphere these photons undergo a multiple Compton scattering (see Section 4) which results in a substantial deviation from the initial axions directions of propagation (Fig 8).

Let us make a simple estimate of the Compton scattering efficiency in terms of the X-ray photon mean free path (MFP) in the photosphere:

$$l = (\sigma_c \cdot n_e)^{-1}$$  \hspace{1cm} (48)

where the total Compton cross-section $$\sigma_c = \sigma_0 = 8\pi r_0^2/3$$ for the low-energy photons [68, 69], $$n_e$$ is the electrons density in the photosphere, and $$r_0 = 2.8 \cdot 10^{-13} \text{ cm}$$ is the so-called classical electron radius.

Taking into account the widely used value of the matter density in the solar photosphere $$\rho \sim 10^{-7} \text{ g/cm}^3$$ and supposing that it consists of the hydrogen (for the sake of the estimation only), we obtain that

$$n_e \approx \frac{\rho}{m_H} \approx 6 \cdot 10^{16} \text{ electron/cm}^3,$$ \hspace{1cm} (49)

which yields the MFP of the photon [68, 69]

$$l = \left(7 \cdot 10^{-25} \text{ cm}^2 \cdot 6 \cdot 10^{16} \text{ electron/cm}^3\right)^{-1} \approx 2.4 \cdot 10^7 \text{ cm} = 2.4 \cdot 10^5 \text{ m}$$ \hspace{1cm} (50)

Since this value is smaller than the thickness of the solar photosphere ($$\sim 10^6 \text{ m}$$), the Compton scattering is efficient enough to be detected at the Earth (see Fig. 8 and Fig. 10 in [36]).

Taking into account the directional patterns of the resulting radiation as well as the fact that the maximum of the axion-originated X-ray radiation is situated near 30 - 40 degrees of latitude (because of the solar magnetic field configuration), the mechanism of the high X-ray intensity bands formation on the Yohkoh matrix becomes obvious. The effect of these bands widening near the edges of the image is discussed in Appendix B in detail.

At the same time it is not too difficult to see that the relative part of the axions $$\Delta_a$$, which practically do not experience the action of the inverse Primakoff effect in the polar ($$\Delta_{pol}$$) and equatorial ($$\Delta_{equ}$$) zones of the solar tachocline (Fig.7d), is a considerable quantity:

$$\Delta_a = \Delta^a_{equ} + \Delta^a_{pol},$$ \hspace{1cm} (51)

If we assume that the equatorial surface ($$S_{equ}$$) formed by two cones going from the center of the Sun, and a part of the sphere with the radius of the Sun ($$R_{Sun}$$) has the dihedral angle of $$\sim 5^\circ$$, it is easy to show that \(^3\)

$$\Delta^a_{equ} = \frac{S_{equ}}{S_{Sun}} \sim 0.05.$$ \hspace{1cm} (52)

\(^3\)This estimate was made on the basis of the numerous computational experiments on magnetic field evolution in the convective zone of the Sun (e.g.[70] and Refs. therein).
It may be shown that the size of the polar zone $\Delta^\text{pol}$ and the equatorial zone $\Delta^\text{equ}$ of the tachocline are equal by the order of magnitude. Hence

$$\Delta_a \sim 0.1.$$  \hspace{1cm} (53)

It means that if the spectral axion flux towards the Earth during the quiet phase of the Sun is described by the expression (44), then in the active phase of the Sun it must also take into account the solar Equator – Poles effect as well as the inverse Primakoff effect:

$$\frac{d\Phi^P_a}{dE} \cong 0.1 + \left[ 1 - \frac{1}{3} P^\text{a+\gamma} \right] 0.9 \frac{d\Phi_a}{dE} = 0.7 \frac{d\Phi_a}{dE},$$  \hspace{1cm} (54)

where the conversion probability $P^\text{a+\gamma} = 1$ in the active phase of the Sun.

## 6 Axion mechanism of Sun luminosity and CAST experiment

In view of the axion mechanism of Sun luminosity, let us analyze below the data of the known experiments on measuring the axion coupling to photon, nucleon and electron for different axion mass ranges.

Virtually all of the major experiments on estimating the limits for the axion-photon coupling constant included the measurement of the axion flux that could be produced in the Sun by the incoherent Primakoff conversion of the thermal photons in the electric and magnetic fields of the solar plasma. The difference between these experiments consisted in the axion flux detection technique only: by the axion-to-photon reconversion (the inverse Primakoff effect) in laboratory transverse magnetic [60, 71–77] and electric (the intense Coulomb field of nuclei in a crystal lattice of the detector plus the Bragg scattering technique [78–81]) fields.

The new constants for the axion mechanism of Sun luminosity, obviously, should be calculated with due regard for the solar equator effect and the Primakoff effect contribution into the total solar luminosity. It is not hard to show that in the general case, according to (54), they should be

$$(g^*_a)^2 = \left[ \Delta_a + \left( 1 - \frac{1}{3} P^\text{a+\gamma} \right) (1 - \Delta_a) \right]^{-1} g^{2}_{a\gamma},$$  \hspace{1cm} (55)

Taking into account the values (53) and the conversion probability in the active phase of the Sun, it is easy to show that the new constant $g^*_a$ is:

$$g^*_a \cong 1.20 g_{a\gamma}$$  \hspace{1cm} (56)

The expression (56) leads to the new limits on the axion-photon coupling, obtained in the CAST and other corresponding experiments, if they were carried out during the active phase of the Sun. Although the change in the axion coupling to a photon with regard to the initial value is rather small, it is crucial for the precise determination of the axion-photon coupling, which plays a fundamental role in the particle physics, astrophysics and cosmology.

## 7 Summary and Conclusion

In the present paper we present a self-consistent model of the axion mechanism of Sun luminosity and TSI variations, in the framework of which we estimate the values of the axion mass ($m_a \sim 10^{-5} \text{ eV}$) and the axion coupling constant to photons ($g_{a\gamma} \sim 7.2 \cdot 10^{-11} \text{ GeV}^{-1}$).

It is necessary to note that obtained estimations can’t be excluded by the existing experimental data because the discussed above effect of solar axion intensity modulation by temporal variations of the toroidal magnetic field of the solar tachocline zone was not taken into account in these observations. On the other hand, the obtained estimates for the axion-photon coupling
cannot be ruled out by the existing theoretical limitations known as the globular cluster star limit \(g_{\alpha\gamma} < 6 \cdot 10^{-11} \text{GeV}^{-1}\), since these values are highly model-dependent. It actually means that the axion parameters obtained in the present paper do not contradict any of the known experimental and theoretical model-independent limitations.

Let us give some major ideas of the paper which formed a basis for the statement of the problem justification, and the corresponding experimental data which comport with these ideas either explicitly or implicitly.

7.1 Axion mechanism of Sun luminosity

One of the key ideas behind this mechanism is the effect of \(\gamma\)-quanta channeling along the magnetic flux tubes (waveguides) in the Sun convective zone (Fig.4). The low refraction (i.e. the high transparency) of the thin magnetic flux tubes is achieved due to the ultrahigh magnetic pressure (see (39)), induced by the magnetic field of about 200-400 T (Fig.3a). It is noteworthy that although such strong magnetic fields have never been used for the explanation or interpretation of the simulation results such as the stability analysis of tachocline latitudinal differential rotation and coexisting toroidal band using an MHD analog of the shallow-water model [35], they have always been present implicitly in the very same simulation results, as our analysis shows. Fig.3a provides an illustrative example where a hidden part of the "latitude – magnetic field of the overshoot tachocline zone" dependence (which is absent on the original plot in Fig.11 of [35]) is added. A right to exist and physical validity of this part is confirmed by the bare fact of its direct correspondence (Fig.3a) with the real X-ray image of the Sun in its active phase (Fig.3b) obtained in the experiments performed with the Japanese X-ray telescope Yohkoh (1991-2001).

The direct experiments on monitoring the space-time evolution of the magnetic flux tubes, rising from the deep layers of the solar convective zone (Fig.1b) proved the existence of the "hollow" ideal magnetic waveguides for \(\gamma\)-quanta. These tubes cross the photosphere and form the solar active regions such as sunspots which are the sources of X-rays (Fig.1d). There are also some theoretical results substantiating the effect of anchoring magnetic flux tubes in the tachocline (Fig.1c).

7.2 Axion mechanism of TSI variation

It is shown that in the framework of the axion mechanism the TSI variations are equivalent to the intensity variations of the \(\gamma\)-quanta of the axion origin which are produced and modulated by the 11-year oscillations of the magnetic field in the solar overshoot tachocline.

It is important to note that the axion mechanism of TSI variations (which means that they are produced by adding the intensity variations of the \(\gamma\)-quanta of the axion origin to the invariant part of the solar photon spectrum (Fig.6b)) easily explains the physics of the so-called Solar Equator – Poles effect observed in the form of the anomalous X-ray distribution over the surface of the active Sun, recorded by the Japanese X-ray telescope Yohkoh (Fig.7,top).

The essence of this effect consists in the fact that the axions that move towards the poles (blue cones in Fig.7, bottom) and equator (blue bandwidth in Fig.7, bottom) are not transformed into \(\gamma\)-quanta by the inverse Primakoff effect, because the magnetic field vector is almost collinear to the axions’ momentum in these regions (see the inset in Fig.7, bottom). Therefore the anomalous X-ray distribution over the surface of the active Sun is a kind of a "photo" of the regions where the axions’ momentum is orthogonal to the magnetic field vector in the solar over-shoot tachocline. The solar Equator – Poles effect is not observed during the quiet phase of the Sun because of the magnetic field weakness in the overshoot tachocline, since the TSI increment of the axion origin is extremely small in the quiet phase as compared to the active phase of the Sun.

In this sense, the experimental observation of the solar Equator – Poles effect is the most striking evidence of the axion mechanism of Sun luminosity and TSI variations. It is hard to
imagine another model or considerations which would explain such anomalous X-ray radiation distribution over the active Sun surface just as well.

7.3 Invisible axions and solar Equator – Poles effect

Obviously, if the axion mechanism of Sun luminosity exists, the new limitations on the axion-photon coupling must be calculated for the future experiments and re-calculated for the old ones taking into account the solar equator effect and the contribution of the inverse Primakoff effect into the total Sun luminosity. This conclusion is extremely important, since the exact value of the axion-photon coupling plays a major role in the particle physics, astrophysics and cosmology.

And, finally, let us emphasize one essential and the most painful point of the present paper. It is related to the key problem of the axion mechanism of Sun luminosity and is stated rather simply: "Is the process of axion conversion into $\gamma$-quanta by the Primakoff effect really possible in the Solar tachocline magnetic field?" This question is directly connected to the problem of the hollow magnetic flux tubes existence in the convective zone of the Sun, which are supposed to connect the tachocline with the photosphere. So, either the more general theory of the Sun or the experiment have to answer the question of whether there are the waveguides in the form of the hollow magnetic flux tubes in the convective zone of the Sun, which are perfectly transparent for $\gamma$-quanta, or our model of the axion mechanism of Sun luminosity is built around simply guessed rules of calculation which do not reflect any real nature of things.

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A Relation between the total and X-ray coronal luminosity variations

The X-ray luminosity of the Solar corona is defined by the following expression:

$$\langle L_X^{\text{corona}} \rangle_{\text{max}} = \int_X \frac{d\Phi_X^{\text{corona}}(E)}{dE} \cdot EdE = \langle E_X \rangle \int_X \frac{d\Phi_X^{\text{corona}}(E)}{dE} dE$$

(A.1)

The total coronal luminosity may be defined as a sum of the X-ray luminosity and the optical luminosity:

$$\langle L_{\text{corona}} \rangle_{\text{max}} = \langle L_X^{\text{corona}} \rangle_{\text{max}} + \langle L_{\text{Optic}}^{\text{corona}} \rangle_{\text{max}} =$$

$$= \langle E_X \rangle \int_X \frac{d\Phi_X^{\text{corona}}(E)}{dE} dE + \langle E_{\text{Optic}} \rangle \int_{\text{Optic}} \frac{d\Phi_{\text{Optic}}^{\text{corona}}(E)}{dE} dE$$

(A.2)

As it follows from Fig. A.1,

$$\langle E_{\text{Optic}} \rangle \approx 10^{-3} \langle E_X \rangle \int_{\text{Optic}} \frac{d\Phi_{\text{Optic}}^{\text{corona}}(E)}{dE} dE \approx 10^6 \int_X \frac{d\Phi_X^{\text{corona}}(E)}{dE} dE$$

(A.3)
Let us substitute these values into Eq. (A.2).

\[
(L_{\text{corona}})_{\text{max}} = \langle E^X \rangle \int d\Phi_{\text{corona}}^X(E) dE + 10^{-3} \cdot \langle E^X \rangle \cdot 10^6 \int d\Phi_{\text{corona}}^X(E) dE = \\
= (L_{\text{corona}}^X)_{\text{max}} + 10^{-3} \cdot 10^6 \cdot (L_{\text{corona}}^X)_{\text{max}} = (L_{\text{corona}}^X)_{\text{max}} + 10^3 (L_{\text{corona}}^X)_{\text{max}} \approx 10^3 (L_{\text{corona}}^X)_{\text{max}}
\]

By analogy,

\[
(L_{\text{corona}})_{\text{min}} = (L_{\text{corona}}^X)_{\text{min}} + 10^3 (L_{\text{corona}}^X)_{\text{min}} = 10^3 (L_{\text{corona}}^X)_{\text{min}}
\]

Then

\[
\Delta L_{\text{corona}} = (L_{\text{corona}})_{\text{max}} - (L_{\text{corona}})_{\text{min}} = 10^3 (L_{\text{corona}}^X)_{\text{max}} - 10^3 (L_{\text{corona}}^X)_{\text{min}} = \\
= 10^3 [(L_{\text{corona}}^X)_{\text{max}} - (L_{\text{corona}}^X)_{\text{min}}] = 10^3 \Delta L_{\text{corona}}
\]

B Explanation of the high X-ray intensity bands widening near the Yohkoh image edges

It is interesting to note that the bands of high X-ray intensity on Yohkoh images deviate from the solar parallels (Fig. 7b). This is especially the case near the edges of the visible solar disk.

This effect may be explained graphically by means of figures B.1 and B.2. These figures show the schematic concept of the Sun image formation on the Yohkoh matrix. Fig. B.2 shows the Sun from its pole.

Let us choose three sectors of equal size on the surface of the Sun (Fig. B.1,B.2). The areas of the photosphere cut by these sectors are also equal \( S_0 = S_1 = S_2 \). However, as it is easily seen in the suggested scheme, the projections of these sectors on the Yohkoh matrix are not of
equal area (Fig. B.1,B.2). The \( S'_1 \) and \( S'_2 \) projections areas are much less than that of the \( S'_0 \) projection (Fig. B.2). It means that the radiation emitted by the sectors \( S'_1 \) and \( S'_2 \) of the solar photosphere and captured by the satellite camera will be concentrated within less area (near the edges of the solar disk) than the radiation coming from the \( S'_0 \) sector (in the center of the solar disk). As a result, the satellite shows higher intensity near the image edges than that in the center, in spite of the obvious fact that the real radiation intensity is equal along the parallel of the Sun.

Therefore, because of the system geometry, the satellite tends to “amplify” the intensity near the image edges, and the areas that correspond to the yellow and green areas at the center (Fig. 7b) become red near the edges, thus leading to a visible widening of the high intensity
bands.

A particularly high radiation intensity near the very edges of the visible solar disk, observed even during the quiet phase of the Sun (Fig. 7a), indicates a rather “wide” directional radiation pattern of the solar X-rays.

Let us make a simple computational experiment. We will choose a sphere of a unit radius and spread the points over its surface in such a way that their density changes smoothly according to some dependence of the polar angle (θ). The azimuth angle will not influence the density of these points. For this purpose any function that provides a smooth change of the density will do. For example, this one:

\[
\rho(\theta) = \left[\rho_0 + \rho_{\text{max}} \cdot \cos(2 \cos(\theta))\right]^{-1}.
\]

(B.1)

Here we take \(\rho_0 = 3.5\) and \(\rho_{\text{max}} = 3\) in arbitrary units. The graphical representation of this dependence is shown in Fig. B.3.

![Graphical representation of Eq. (B.1).](image)

I.e. it yields a minimum density of the points near the poles and the equator, and the maximum density of the points near \(\theta = 60^\circ\) and \(\theta = 120^\circ\).

The polar angle \(\theta\) was set in the range \([0, 180^\circ]\) with the step of 1°. The azimuth angle \(\varphi\) was set in the range \([0, 180^\circ]\) (one hemisphere) with a variable step \(\Delta \varphi\) representing the variable density, since the points density is inversely proportional to the step between them (\(\Delta \varphi \sim 1/\rho\)). We assume that

\[
\Delta \varphi(\theta) = \Delta \varphi_0 + \Delta \varphi_{\text{max}} \cdot \cos(2 \cos(\theta)) \quad \text{[deg]}
\]

(B.2)

The values of \(\Delta \varphi_0 = 3.5^\circ\) and \(\Delta \varphi_{\text{max}} = 3^\circ\) were chosen arbitrarily. So,

\[
\Delta \varphi(\theta) = 3.5 + 3 \cdot \cos(2 \cos(\theta)) \quad \text{[deg]}
\]

(B.3)

From Eq. (B.3) it is clear that the minimum step was 0.5° and the maximum step was 6.5°. Apparently, the more is the step, the less is the density (near the poles and the equator) and vice versa, the less is the step, the more is the points density. This was the way of providing a smooth change of the points density by latitude (along the solar meridians).

Obviously, this forms the “belts” of high density of the points along the parallels. The projection of such sphere on any plane perpendicular to its equator plane will have the form shown in Fig. B.4a. As it is seen in this figure, although the density does not depend on azimuth angle, there is a high density bands widening near the edges of the projected image. These bands are similar to those observed on the images of the Sun in Fig. B.4b.

Let us emphasize that the exact form of the dependence (B.2) as well as the exact values of its parameters were chosen absolutely arbitrarily for the sole purpose of the qualitative effect demonstration. They have no relation to the actual latitudinal X-ray intensity distribution over the surface of the Sun.
Figure B.4: a) Simulation of the high intensity bands formation on the 2D projection of the sphere. b) Sun X-ray image from Yohkoh satellite during the active phase of the Sun.

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