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OVERLOOKED ASTROPHYSICAL SIGNATURES OF AXION(-LIKE) PARTICLES

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ABSTRACT

We discuss solar signatures suggesting axion(-like) particles. The working principle of axion helioscopes can be behind unexpected solar X-ray emission. Because this is associated with solar magnetic fields ($\sim B^2$), which become in this framework the catalyst and not the otherwise suspected / unspecified energy source of solar X-rays. In addition, the built–in fine tuning we may (not) be able to fully reconstruct, and, we may (not?) be able to copy. Solar axion signals are transient brightenings, or, continuous radiation violating the second law of thermodynamics and Planck's law of black body radiation. To understand the corona problem and other mysteries like flares, sunspots, etc., we arrive at two exotica: a) trapped, radiatively decaying, massive axions allow a continuous self-irradiation of the Sun, explaining the sudden temperature inversion ~2000 km above the surface and b) outstreaming light axions interact with local fields ($\sim B^2$), depending crucially on the plasma frequency which must match the axion rest mass, explaining the otherwise unpredictable transient solar phenomena. Then, the energy of a related phenomenon points at the birth place of involved axions. For example, this suggests that the ~2 MK solar corona has its axion roots at the top of the radiative zone. The predicted $B \approx 10$–50 T make this place a coherent axion source, while the multiple photon scattering enhances the photon-to-axion conversion unilaterally, since axions escape. We conclude that the energy range below some 100 eV is a window of opportunity for axion searches, and that it coincides with a) the derived photon energies for an external self-irradiation of the Sun, which has to penetrate until the transition region, and b) with the bulk of the soft solar X-ray luminosity of unknown origin. Thus, indirect signatures support axions or the like as an explanation of enigmatic behaviour in the Sun and beyond. Axion antennas could take advantage of such a feed back.

1. Introduction

With the ongoing direct search for (solar) axions [1] one can ask whether the same detection principle is at work behind certain mysterious solar or other astrophysical observations. Indirect signatures for dark matter particle candidates might be strong, if, for example, the same process(es) can explain consistently more celestial phenomena. Here we mainly discuss striking solar observations of unknown origin which seem to require the involvement of axions or other exotica with similar properties. Previous work [2–4] addressed a steady X-ray emission due to very few gravitationally trapped massive axion-like particles (about 1 in 10^7, or only ~100 *kg*/s since 4.6 Gyears), giving rise to a self-irradiation of the whole Sun. In this work, we mainly argue in favour of a second solar X-ray component expected to originate from the widely accepted interaction of light axions or the like with the inner/outer solar magnetic fields, as they stream out of the Sun. In this work we emphasize the ubiquitous solar magnetic field, which is the dominating "element" in all axion experiments.

2. Astrophysical signatures

<u>The solar corona problem:</u> Stellar observations and theory of stellar evolution cannot be reconciled with stars having atmospheres that emit X-rays [5], suggesting the question: Where do these X-rays come from? The mechanism that heats the solar corona to some MK has remained elusive since its discovery in 1939. The solar corona problem is one of the most important and challenging problems in astrophysics [6], since it violates, at first sight, the second law of thermodynamics, which is actually improbable. The radiative decay of gravitationally trapped massive particles like the generic Kaluza–Klein axions, being created by the Sun itself, could provide the invisible source that sustains the self-heating of the solar atmosphere [2], thus reconciling observation and thermodynamics. In fact, the expected decay hard X-rays from massive

axions, accumulated around the Sun since cosmic times, fit only the energetic part (above ~2 keV) of the reconstructed analog photon spectrum from the quiet Sun during solar minimum (see Figure 8 and 9 in ref. [2]). However, this is only one X-ray component within the axion scenario, and probably the weakest one.
Interestingly, it was shown in ref. [3] that the radial distribution of the two off-pointing observations with the YOHKOH X-ray satellite fit the massive axion scenario also in the low–energy range (~0.5–4 keV), thus suggesting more measurements of this kind. In fact, the RHESSI mission has recently repeated several off-pointing observations above the solar limb during non-flaring, spotless and active-region-free Sun, i.e., during quiet Sun conditions [7], arriving apparently at a hard X-ray spectrum, which is rather similar to the reconstructed one from YOHKOH measurements in the previous solar cycle minimum (see Figure 9 in ref. [2]). The values obtained with RHESSI in the ~3–12 keV range, for such extremely quiet periods at the present solar minimum phase, correlate with those from another orbiting X-ray solar telescope (GOES), implying a real signal in this actually not so low energy band [7,8] for a cool Star like our Sun. This we consider as additional supporting evidence for the (massive) solar axion scenario [2]. Because, a conventional explanation with electrons raises a new problem: How is such a population of energetic electrons created in the quiet corona?

<u>Magnetic field related observations:</u> The long lived massive axion(-like) particles can not explain:

a) local and transient solar phenomena, and
b) the prevailing soft X-ray emission, which makes the bulk of the solar X-ray luminosity during periods of quiet (see Figure 9 in ref. [2]) as well as active [i.e. flaring] Sun.

Therefore, an as yet unnoticed additional X-ray source must be at work. The Primakoff–effect with "conventional" axions, e.g. like the QCD-motivated ones, can interact inside the solar magnetic fields, which is after all the most natural process to expect, as it resembles the working principle of an axion helioscope like CAST. Thus, near the solar surface X-rays should also be emitted due to magnetic-field-induced radiative "decay" of outstreaming axions (see below). Depending on the relative intensity of converted light axions, the resulting radial distribution of X-rays, coming from both components near the surface of the Sun, can be different from that expected for massive ones only [2,3]. Interestingly, the available two off-pointing observations with YOHKOH [3] show a radial distribution that agrees within ~30% with the massive axion simulation. Therefore, in our heuristic approach explaining the otherwise unexpected solar X-rays with axions or the like, this second magnetic–field–related component offers a possible explanation also for this rather small but significant discrepancy.

There is strong observational evidence that (transient) solar X-ray emission correlates with the local magnetic field strength squared (~B^2) [9], which is characteristic for light axion involvement, and, it determines the performance of an axion helioscope [1] à la Pierre Sikivie, and, à la Karl van Bibber *et al.*. Actually in all axion experiments, the B^2 - dependence of a potential signal is generally accepted as the ultimate method for axion identification. Large–scale magnetic fields of several kGauss exist in the enigmatic sunspots, which show enhanced and unpredictable activity. Interestingly, it is known that the magnetic field somehow heats the quiet solar corona, with the exact energy release mechanism still enigmatic in solar physics; within the axion picture, this is naturally expected. A few magnetic–field–related cases in favour of the axion(-like) scenario have already been discussed in ref. [9]. For completeness, we repeat some of them here briefly in an updated form (see also ref. [9]):

a) The X-ray emission from an isolated solar active region, measured with YOHKOH's X-ray telescope, during non-flaring periods, shows a striking $B^{1.94\pm0.12}$ dependence in the range ~0.5–4 keV; within the axion scenario, this points at a low energy solar axion spectrum (below ~ 1 keV), in contrast with the widely used solar axion spectrum that peaks at ~4.2 keV. Such a new component is of utmost interest for the design of direct solar axion searches. Similarly, a plethora of solar soft X-ray flux measurements correlates with the local magnetic field (~B^n), with the exponent $n\approx2$ varying smoothly by ~20% during the solar cycle(!) [10], pointing possibly to a deeper axion implication in the dynamic Sun.
b) Remarkably, above sunspots the corona is hotter (e.g. ~2.1 MK instead of 1.3 MK) and the photosphere just underneath is cooler (e.g. ~4000 K instead of 5770 K) than near quiet Sun regions. Each of these observations is consistent with a Primakoff–effect taking place inside the extended strong surface magnetic fields with the plasma frequency matching the axion rest mass. The emerging picture is: 1) energetic axions streaming out of the hot inner Sun can be converted back to X-rays, further heating–up the preexisting ~1.3 MK quiet Sun corona, and 2) near the photosphere or even deeper into the Sun, photons with energy below ~10–100 eV can undergo the reverse Primakoff–process escaping into axions or the like, thus making the photosphere cooler.

c) Generally, there is strong evidence that magnetic elements in the Sun with higher magnetic flux are less bright [11]. Low–energy solar axion production due to surface magnetic fields fits the observed $\sim B^2$-dependent dimming effects of the sunspot brightness in the visible. Also recently [12], some 900 sunspots have shown an increase in brightness while the magnetic field strength was decreasing. Then, the dark sunspots can be low–energy axion sources, whose strength should correlate with their level of darkness, thus providing an axion trigger [13]. To be more quantitative, we work out here a ***numerical example:*** We use the PVLAS derived parameters, i.e. $g_{a\gamma\gamma} \approx 2.5\ 10^{-6}$GeV^{-1} and $m \approx 1$ meV. We take as a mean free path length of visible photons in the photosphere equal to ~100 km, which is equal to the coherence length of the photon-to-axion conversion; the condition $\hbar\omega_{plasma} \approx mc^2 \approx 1$ meV seems reasonable. For a sunspot magnetic field $B \approx 3$ kGauss (see ref. [21]), and, provided the PVLAS finding is correct, we estimate a 'photon-to-axion' conversion efficiency $P_{\gamma a} \approx 0.001$. Furthermore, assuming a surface of a single sunspot of a few ‰ of the solar surface, the expected solar axion-like luminosity is $L_{axion} \approx 10^{28}$erg/s. The derived signal rate in the visible, applying CAST performance [1], is $S \approx 300$ Hz. Such a high signal rate along with the rather conservative values we used, allow to be sensitive to a much smaller coupling constant and check the PVLAS result.

In summary, axion–photon oscillations depend a) on the squared transverse magnetic field component along the axion/photon propagation, b) on the local plasma density, since at resonance $\hbar\omega_{plasma} \approx m_{axion}c^2$ the coherence length is limited by the photon absorption, and c) on the magnetic field configuration. Note that each of these parameters changes permanently near the solar surface and also deeper inside the turbulent (i.e. boiling) convective zone. For a quantitative calculation, since it implies restless density fluctuations for any place above the radiative zone ($R > 0.7 \cdot R_{solar}$), it is crucial to know this dynamical behaviour; resonance can be restored temporally repeatedly covering a large bandwidth in axion rest mass, e.g., ~0-10 eV/c^2, if we take as maximum density the one near the bottom of the convective zone. Then, axion (dis)appearance is not at all a static process; it can be the cause of the unpredictable dynamical behaviour of the Sun from the visible to X-rays. In fact, such a rapid change of the axion-relevant parameters defines instantly certain volume elements, where resonance-coherence effects can result in an enhanced axion production as well as in axion-related brightenings or light dimming. Note that a fine tuning is also exercised in CAST Phase II, by changing the density of the refractive gas in the magnetic volume [1].

Flares: What produces solar flares and Coronal Mass Ejections is one of the great solar mysteries. However, the energy that powers them is generally believed to be (connected to) the magnetic field [14]. Following recent work [15], these strong X-ray emitting events correlate (within 1.8σ) with the solar surface magnetic field-squared (see Figure 1). In fact, our fit to the X-ray data gives a $\sim B^{1.6\pm0.22}$ dependence, while the authors in ref. [15] refer even to a B^2 correlation, fitting the assumed axion scenario.

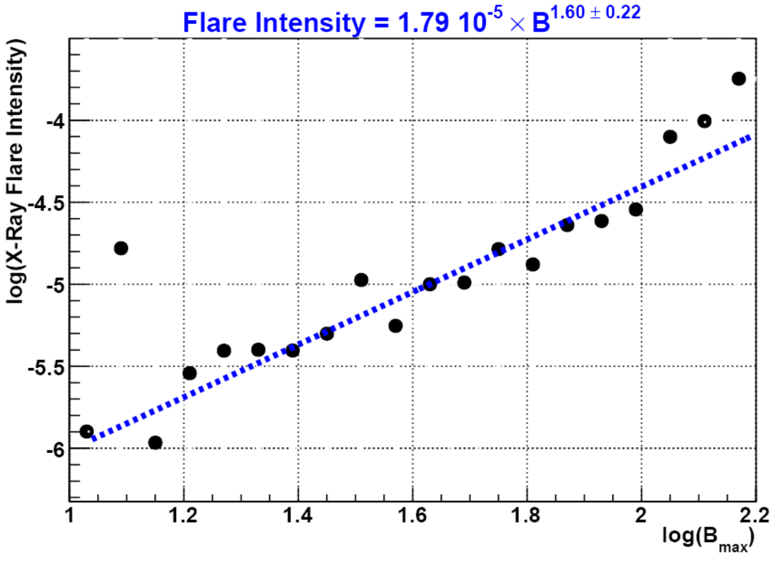

Figure 1 Rebinned peak flare X-ray intensity vs. the maximum magnetic field (B_{max}), reconstructed from ref. [15]. The blue dashed line gives the derived fit to the data points ($\sim B^{1.6\pm0.22}$).

Note that the conventional solution for this radiation emission is that the hard X-rays are coming from electrons. However, this leads to the electron "problem" [16], since the energetic electron flux must be ~10^5 times higher than the X-rays. We stress here that within the axion scenario the local surface magnetic field is "only" the required catalyst for the axion–photon reactions to take place, and not the otherwise suspected / unspecified energy source of solar X-rays. In this framework, the inner Sun is the actual energy source that creates the outstreaming axions.

3. Solar magnetic fields

We recall that it is the macroscopic coherence effects in magnetic axion helioscopes [1] which result in a better axion-to-photon conversion than in detectors, where the axions interact incoherently with the detector atoms. Therefore, helioscopes are more sensitive to axions. Surprisingly, solar magnetic fields [17] have not been included in the model calculations of the axion production rate. However, inside the magnetic Sun, when the local plasma frequency fits the axion rest mass, photon–axion conversion might even be the dominant axion production channel, since the coherence length can be maximum, i.e., equal to the photon mean free path. This is ~1 mm in the core and ~100 km (!) at the photosphere. Such an additional solar axion production channel can modify the previously expected solar axion spectrum (its intensity and its shape) without taken into consideration magnetic fields [18]. To know this is of utmost importance in interpreting solar observations as well as in adopting the appropriate parameter values for optimum performance of an axion antenna.

Interestingly, strong magnetic fields outside the hot core, like the simulated ones in Figure 2, can selectively enhance the production of low(est) energy axions. More precisely, in this scenario, the soft quiet Sun X-ray luminosity (from the celebrated ~2 MK corona) could originate from converted massive or light axions due to their spontaneous or "induced" decays, respectively, both kinds of axions stemming from a shell between the radiative and the convective zone ($R \sim 0.7\, R_{solar}$); since it has the required temperature of ~2 MK [19] and is permeated with a predicted ~ 30-50 Tesla magnetic field (see Figure 2), this is a potential source of low–energy axions. The same reasoning applies to other potential candidates, e.g. microflares with a mean temperature of 12.6 MK [20], including large flares whose temperature distribution is, remarkably, around ~15-20 MK. It is also interesting to note that the power of flares, extrapolated on the whole solar surface, does not actually exceed the total solar luminosity [20]. This is not a signal, but it fits with the heuristic picture we follow with flares too, while in the opposite case, the reasoning would have been negative.

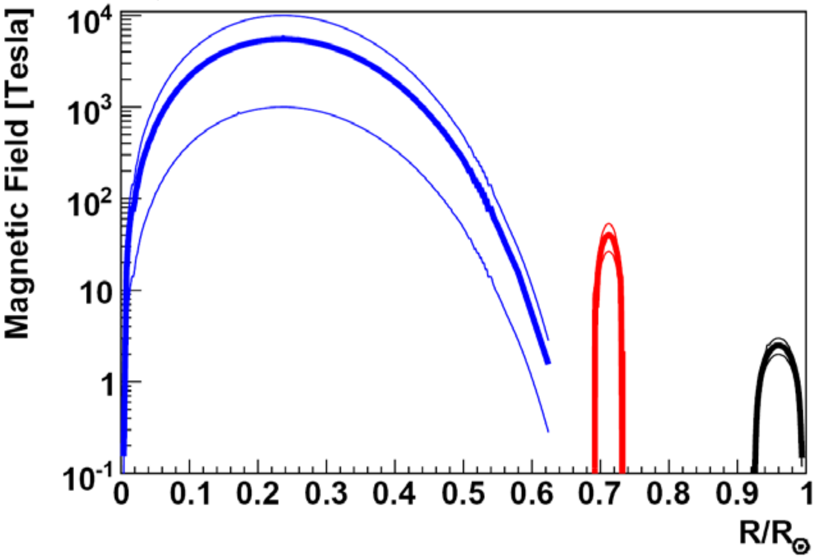

Figure 2 The reconstructed solar magnetic field simulation from ref. [17]: 10^3–10^4 Tesla (left), 30–50 Tesla (middle) and 2–3 Tesla (right), with a temperature of ~9 MK, ~2 MK and ~200 kK, respectively. The thin lines show the estimated range of values for each magnetic field component. Internal rotation was not included in the calculation. An additional axion production at those places can modify both intensity and shape of the solar axion spectrum (Courtesy Sylvaine Turck-Chièze).

We stress that a few 100 eV massive axions of the Kaluza–Klein type might also be created coherently, since the many axion mass states allow a quasi continuous resonance crossing throughout the magnetic Sun, which is a unique fine tuning, only if Kaluza–Klein-like axions exist. If these less massive axions (see ref. [2]) build up a large trapped component around the Sun, even their spontaneous decay alone could explain the low–energy X-rays from the quiet Sun. The induced "decay" in magnetic fields of light axions at the same lower energy range, created probably in the same place, comes in addition. In favour of this conclusion we recall the following findings:

a) the quiet Sun soft X-ray intensity is increasing at lower energies and its origin is unknown,
b) the measured radial distribution of the two off-pointing observations with YOHKOH (~0.5–4 keV) actually supports such a less massive axion scenario, which was not covered in ref. [2],
c) in order to reach the depth of the solar transition region (at ~2000 km) of the Sun being externally self-irradiated from decaying axions orbiting around the Sun, the estimated photon energies were ~50–350 eV [2], which is exactly the energy range of the ~2 MK solar corona radiation.

So far, the estimated X-ray luminosity due to the generic massive solar axions was even strongly suppressed below ~1 keV [2], since their assumed birth place was the ~16 MK hot solar core. Therefore, it seems that magnetic fields might be one of the key parameters for the solar axion scenario that accommodates light as well as massive axions or the like. Furthermore, local magnetic fields up to ~0.6 Tesla have been measured at the surface of sunspots [21], where axion-to-photon oscillations and vice versa can take place and cause otherwise unexplained phenomena. Then, the whole Sun is a multicomponent axion source.

4. Discussion - Conclusion

Challenging questions like the origin of the soft and hard solar X-ray emission remain elusive within conventional astrophysics, with the solar corona problem being present ~70 years. Also, it has been known for many years that the magnetic field plays a crucial role in heating the solar corona, with the exact energy storage and release mechanism(s) being still a nagging unsolved problem for solar physics [22]. In this work, supporting evidence has been presented in favour of a second, magnetic–field–related solar X-ray component, which can originate from converted axions streaming out of the Sun, explaining thus also transient solar X-ray emission.

We also mention briefly other unpredictable X-ray observations, which seem to be of potential relevance for axions or the like: class 0 protostars [23]; the galactic centre, the Inter Cluster Medium, the ubiquitous X-ray background radiation [4]; the Fourier analyzed data of solar neutrinos and soft X-rays result in surprisingly identical frequencies [24]; the solar metallicity problem [25], i.e., the disagreement of the Ne/O abundance between solar model prediction and observation, could be due to an axion surface effect. Following Martin Asplund, a pioneer of this discovery, "one possibility is rather the extra heating from the X-ray absorption of converted axions in the atmosphere which might increase the temperature in the spectral line formation region of the Sun" [26].

Finally, combining all these kinds of signatures, one might be able to constrain the appropriate parameter values in direct axion searches with Earth-bound experiments. One first practical conclusion is that axion helioscopes should lower their threshold energy below a few 100 eV, following the scenarios with (a few 100 eV) massive and light axions as being co-responsible for the dominant and otherwise unexplained X-ray emission in this energy range, from the quiet and the active Sun alike. The axion signatures discussed remained unnoticed before, probably because of their multifaced appearance like QCD-inspired axions, massive Kaluza–Klein axions, or other exotic forms which have not yet been predicted.

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