Guidelines for axion identification in astrophysical observations

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Abstract

The origin of various celestial phenomena have remained mysterious for conventional astrophysics. Therefore, alternative solutions should be considered, taking into account the involvement of unstable dark-matter particle candidates, such as the celebrated axions or other as yet unforeseen axionlike particles. Their spontaneous and induced decay by the ubiquitous solar magnetic fields can be at the origin of persisting enigmatic X-ray emission, giving rise to a steady and a transient/local solar activity, respectively. The (coherent) conversion of photons into axion(-like) particles in intrinsic magnetic fields may modify the solar axion spectrum. The reversed process can be behind transient (solar) luminosity deficits in the visible. Then, the Sun might be also a strong source of \sim eV-axions. The linear polarization of photons from converted axion(-like) particles inside magnetic fields is very relevant. Thus, enigmatic observations might be the as yet missing direct signature for axion(-like) particles in earth-bound detectors.

1 Introduction

The direct and indirect detection of axions [\[1\]](#page-9-0) or other particles with similar properties is ongoing [\[2\]](#page-9-1). In view of the published and upcoming data in the range of photon energy of $\sim 10^{-4}$ eV to $\sim 10^{4}$ eV, some guidelines are given in this note, covering a wide band of the potential participation of axions or axion-like particles in astrophysical observations of unknown origin. In order to show the diversity and the complexity associated with the involvement of exotic particles in such processes, some examples demonstrate best how possible signatures (will) make their appearance. Note, only striking astrophysical phenomena with missing conventional explanation are addressed, being thus suggestive for an alternative solution. The reservoir of the exotic dark matter particle candidates is huge, since they make some 25% of the mass-energy balance of the Universe. This work is by no means complete, since it refers only to those observations, which fit the axion-scenario: a) radiatively decaying particles (e.g. $a \rightarrow \gamma + \gamma$), or penetrating particles which can be produced in the reversed process $(\gamma + \gamma \rightarrow a)$, and b) materialization of such exotica inside electric/magnetic fields [\[3\]](#page-9-2).

The purpose of this work is to summarize some of the most relevant findings, which are in support of the axion scenario. This might also help to avoid misinterpretation of observations. We start with the atmosphere of the nearby Sun. The similar-to-Sun logic has sneaked in stellar physics work, but care should be taken to avoid wrong extrapolations, because of the many unexplained solar phenomena. In addition, the ongoing direct search for light axions (e.g. [\[4\]](#page-9-3)) is based on principles, which could already be at work in stars, solving the remaining nagging problem [\[5\]](#page-9-4) of how solar/stellar magnetic energy is converted to heat and other forms. Within the axion scenario, the magnetic field is not the energy source, but the catalyser, which transforms exotic axion(-like) particles streaming out of the stellar core into X-rays.

2 Some examples from the sun and beyond

A) It was suggested in ref.s [\[6,](#page-9-5) [7,](#page-9-6) [8\]](#page-9-7) that the spontaneous radiative decay of gravitationally trapped massive particles of the type Kaluza-Klein axions might explain a constant component of the (quiet) Sun X-ray luminosity; its radial distribution can provide an additional signature of such processes coming thus from long lived and non-relativistic particles accumulated over cosmic time periods around their place of birth, e.g. the Sun.

The recently derived limits, in the \sim 3 - 17 keV energy range, for the quiet *and* spotless Sun by RHESSI observations [\[9\]](#page-9-8) along with measurements from the 1960's, seem to be an interesting result for the solar axion scenario: "we can immediately see the very small signal from the quiet Sun", which is not necessarily (much) smaller than the ones used in ref.'s $[6, 7]$ $[6, 7]$.

B) It is known that the ubiquitous solar magnetic field plays a crucial role in heating the corona, but the exact mechanism is still unknown [\[10\]](#page-9-9). However, the working principle of the ongoing direct search for almost massless (solar) axions [\[4\]](#page-9-3) can be at work also in Stars, solving the persisting question of how magnetic energy is converted there to heat or other forms [\[5\]](#page-9-4). Resonance-like behaviour between matter density and axion restmass in the presence of a magnetic field can occasionally enhance or suppress the axion $\leftrightarrow \gamma\gamma$ process [\[11\]](#page-9-10). The reconstruction of such effects might allow to understand the dynamical character, i.e. the otherwise unpredictable nature of the various kind of solar transient brightenings or deficits, in X-rays or in the visible, respectively.

C) In earlier observational work of the corona [\[12,](#page-10-0) [13,](#page-10-1) [14\]](#page-10-2) it was concluded that the solar corona is heated by two (independent from each other) components: a) The basal heating all over the quiet and active Sun, and b) The transient heating owing to magnetic field effects. Also ref. [\[14\]](#page-10-2) arrived at the same quantitative conclusion: there must be a steady heating mechanism of the non-flaring Sun and an independent mechanism for heating the flares, whatever their size. The understanding of how energy is released in (solar) flares remains a central question in astrophysics [\[15,](#page-10-3) [16\]](#page-10-4). Thus, the unexpectedly hot and mysterious solar corona requires two heating components. Within the axion scenario, this finding might point to the involvement of two kind of exotica, being behind these two components: 1) particles like the celebrated light axions, which are converted to photons inside the microscopic or macroscopic surface electric/magnetic fields via the Primakoff effect. The changing local magnetic fields are then at the origin of the transient component of the X-ray emission, its topology on the solar disk, etc. 2) radiatively decaying long-lived massive particles like the generic axions of the Kaluza-Klein type.

The ratio of the X-ray intensity from these two axion-sources is not constant as it depends on the solar cycle due to the varying solar magnetic field [\[2\]](#page-9-1).

D) A strong intrinsic magnetic field (see for example ref. [\[17\]](#page-10-5)) may well modify the shape and intensity of the (solar) axion energy spectrum, e.g. enhancing energies below $\sim 1 \text{ keV}$ [\[2\]](#page-9-1). This might imply a dominant coherent axion production in solar magnetic fields outside the widely assumed axion source at the hot core, enhancing thus the production of low energy axions with a rest mass following the local plasma frequency (ω_{pl}) [\[2\]](#page-9-1). For example, the generic Kaluza-Klein tower axion mass states allow the otherwise selective resonance-crossing production [\[11\]](#page-9-10) to take place at any solar density, since some of the axion rest mass states will always satisfy the relation $-\hbar\omega_{pl} \approx$ $m_{axion}c^2$. Once this condition is fulfilled, the associated oscillation length can be equal to the photon mean free path length, which is not negligible: from a few cm in the core to ∼ 100 km in the photosphere. Taken into account the dynamical behaviour of relevant solar parameters outside the solid core, like magnetic field, density, etc., the resonance-crossing might be there at work temporally and/or locally. This might explain the transient character of solar X-ray emission, or, the deficit in the visible due to the disappearance of photons into ∼ eV-axions via the Primakoff effect; the solar surface becomes then a strong lowest energy axion source.

Therefore, for signal identification, the knowledge of the ever changing solar magnetic environment, where the axion-to-photon oscillations can take place (in both directions), is crucial. In favour of the axion scenario is the expectedly observed striking B^2 -dependence of the soft X-ray intensity from a single solar active region [\[18\]](#page-10-6), where the magnetic field strength reaches temporally some kGauss (see also ref. [\[19\]](#page-10-7)). This can be seen as strong evidence in favour of a time-varying heating component of the solar corona due to axion-to-photon conversion via the Primakoff effect inside the surface magnetic fields (see also [\[2\]](#page-9-1)). The mentioned observation by RHESSI of hard X-ray emission from non-flaring solar active regions supports further a magnetic field related component of the solar axion scenario [\[9\]](#page-9-8).

E) Large axion-to-photon oscillation lengths. The coherence or oscillation length is very long only for very small axion masses and hence very low coupling values. One way to circumvent this problem is to assume magnetic fields that change polarity along the oscillation path. This method is of course of limited use since the axion mass and the magnetic field need to artificially finely tuned so that the axion-to-photon oscillation length matches the magnetic field oscillation length. An alternative and more promising approach is presented here.

The axion-photon mixing occurs in the magnetic field and the propagating eigenstate is the mixed state. This mixed state can be destroyed by an index of refraction, both the real and imaginary parts. The presence of a gas in, e.g., star that its density is not homogeneous can cause the spatial splitting of the mixed state. Only the photon will refract, whereas the axion will not, thus splitting the mixed state. On the other hand the imaginary part of the index of refraction means that the photon is absorbed by the atomic/molecular gases and then re-emitted. The newly emitted photon need not be emitted in the same wavelength and/or direction as the original one, again splitting the mixed state.

In order to gain from this effect in the overall axion-to-photon oscillation we need to require that the gas density is such that the required refraction effects happen within a length $l \leq L/2$, with L being the oscillation length. Overall then a much longer effective length than previously assumed can be available, be it in laboratory helioscopes or at the outer Sun, applying equally from X-rays to photons in the visible.

To be more specific, let us take an oscilation length of ~ 1 cm or \sim 100 km. The advantage with such a refractive place is that this coherence can be at work repeatedly over, say, ∼1000 km to ∼100000 km, making thus an astrophysical environment a very efficient axion-catalyser, at least occasionally.

F) The Sunyaev-Zeldovich (SZ) Effect in Clusters of Galaxies. The decrement due to the SZ effect derived recently from 31 co-added Clusters of Galaxies accounts only for about $1/4$ of the expected value [\[20\]](#page-10-8). The radiative decay of even a small fraction of the dark matter constituents there, which provide the gravitational well at those places of the Universe, can mimic a non-existing plasma [\[8\]](#page-9-7). Thus, the derived properties for the Inter Cluster Medium based partly on its X-ray emission can be modified in an actually unpredictable way (see below). Therefore, the claimed discrepancy, IF correct, it can be a signature for an axion(-like) scenario. It is worth noticing that the authors of ref. [\[20\]](#page-10-8) were not biased to find less matter out there, but rather the opposite, i.e. to localize any extra baryonic matter at those places. The generic massive axions of the Kaluza-Klein type fit this finding.

G) The ∼ 8 keV diffuse hot plasma at the Center of our Galaxy remains

enigmatic, since it should escape the gravitational well. Again, the radiative decay of gravitationally captured massive particles can mimic a non-existing plasma component, while the real baryonic plasma component can be not as hot as widely assumed. This is an alternative explanation, which demonstrates the potential imprint of axion-like particles as they have been worked out only for the case of our Sun [\[6,](#page-9-5) [8\]](#page-9-7).

H) Linear polarization of photons if they come from converted axions inside a transverse magnetic field. This property can provide an additional and strong support for the axion(-like) scenario. For example, on extreme large scales, the optical polarization measured from 355 Quasars is of potential relevance for the reasoning of this work [\[21,](#page-10-9) [22\]](#page-10-10). Because, it reflects remarkably a behaviour as it is expected from photon-pseudoscalar oscillations inside intervening magnetic fields, as it is concluded in ref. [\[21\]](#page-10-9).

Going back to the nearby sunspots, the observed broad-band circular and linear polarization [\[23\]](#page-10-11) along with their center-to-limb progression throughout the sunspot might be of direct relevance. It is interesting to note that ref. [\[24\]](#page-10-12) concludes that "the maximum polarization occurs where the average magnetic field is perpendicular to the line of sight", while it is mentioned that "the polarization of sunspots remains to be explained". Finally, from ref. [\[25\]](#page-10-13) it follows that there is a correlation between the broad-band circular and linear polarization.

3 Conclusion

The otherwise unexpected (solar) X-rays from a relatively cool star like our Sun [\[26\]](#page-10-14) could be used as input in other places in cosmos. So far, the shape of the solar X-ray spectrum and in particular the strong low energy part can be reconstructed only partly by the massive axion(-like) scenario. An enhanced Primakoff effect inside the Sun might be behind the sub-keV X-rays from the

(quiet) Sun. The mentioned magnetic field related axion-photon conversion (inside/outside the Sun) might be the key in reaching more insight of such exotic phenomena in the nearby Sun, allowing to speculate on far reaching consequences of axion-telescopes like the Cern Axion Solar Telescope (CAST) [\[4\]](#page-9-3), and, the X-ray observatories in orbit.

The widely accepted point of view that dark matter particles do not emit or absorb electromagnetic radiation does not hold for radiatively decaying particles like the generic massive axions of the Kaluza-Klein type, while observational evidence in favour of their existence is being accumulated. Thus, some axion(-like) dark matter constituents were never dark, but we may simply have overlooked them.

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