Axions, photons with external Magnetic or Axion Fields

E.Guendelman,
Ben Gurion U. , Israel,
Beyond the Standard Model
VARADERO, CUBA, MAY 2015

The Axion (or ALP) Photon System is described by the action

$$S = \int d^4x \left[-\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m^2 \phi^2 - \frac{g}{8} \phi \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta} \right].$$

Then we want to consider two types of external fields

- 1. An external Magnetic Field, we will see that the theory build on small perturbations will describe axion-photon oscillatons, beam spitting beautifully described by an effective scalar QED like formalism
- 2 . An external Axion Field, space or time dependent. For a time dependent axion, a cosmological application is found, leads to tachyonic mass generation for the photon.

This could be related to a variety of effects, including

Baryogenesis in the early universe and

Lorentz violating effects.

For a space dependent axion, there is anisotropic mass generation for the photon

Can be applied in heavy ion collisions or effects in the boundary of a neutron star, which could afect the cooling properties, if the axion condensate exists near the surface of such star for example.

Consider an external magnetic field pointing in the x direction with magnitude B(y,z).

For small axion and photon perturbations which depend only on y, z and t, consider only up to quadratic terms in the perturbations.

Then the axion photon interaction is

$$S_I = -\int d^4x\,[\beta\phi E_x],$$

where $\beta = gB(y,z)$. Choosing the temporal gauge

- Considering also only x polarizations of the photon, since only this polarization couples to the axion and to the external magnetic field, we obtain that (A represents the x-component of the vector potential)

$$E_x = \quad -\partial_t A$$

Ignoring integration over x (since everything is taken to be x-independent), we obtain the effective 2+1 dimensional action

$$S_2 = \int dy\, dz\, dt \left[\frac{1}{2}\partial_\mu A \partial^\mu A + \frac{1}{2}\partial_\mu \phi \partial^\mu \phi \qquad - \frac{1}{2} m^2 \phi^2 + \beta \phi \partial_t A \right]$$

Neglecting the mass of the axion, which gives O(2) symmetry in the kinetic term between photon and axion, performing an integration by parts in the interaction part of the action that gives the O(2) symmetric form for the interaction in the case the external magnetic field is static

$$S_I = \frac{1}{2}\int dy\,dz\,dt\,\beta\left[\phi\partial_t A - A\partial_t\phi\right]$$

In the infinitesimal limit there is an Axion Photon duality symmetry (0rdinary rotation in the axion photon space), here epsilon is an infinitesimal parameter

$$\delta A = \epsilon\phi, \qquad \delta\phi = -\epsilon A$$

Using Noether`s theorem, we get a conserved charge out of this, the charge density being given by

$$j_0 = A\partial_t\phi - \phi\partial_t A - \frac{\beta}{2}\left(A^2 + \phi^2\right)$$

Defining a complex scalar field

$$\psi = \frac{1}{\sqrt{2}}(\phi + i\,A),$$

We see the to first order in the external field the axion photon system interacts with the charge density which is like that of scalar electrodynamics

$$j_0 = i(\psi^* \partial_t \psi - \psi \partial_t \psi^*) - \beta \psi^* \psi$$

In the scalar QED language, the complex scalar creates particles with positive charge while the complex conjugate creates antiparticles with the opposite charge. The axion and photon fields create however linear contributions of states with opposite charges since

$$\phi = \frac{1}{\sqrt{2}}(\psi^* + \psi), \qquad A = \frac{1}{i\sqrt{2}}(\psi - \psi^*)$$

The Scalar QED Picture and its consequences

1. gB(y,z) couples to the “density of charge” like an external electric potential would do it.
2. The axion is a symmetric combination of particle antiparticle, while the photon is the antisymmetric combination.
3. If the direction of initial beam of photons or axions is perpendicular to the magnetic field and to the gradient of the magnetic field, we obtain in this case beam splitting (new result).
4. Known results for the cases where the direction of the beam is orthogonal to the magnetic field but parallel to the magnetic field gradient can be reproduced easily.

For present experiments for axion detection, B=B(z),axion and photon = f (t,z) (for example CAST)

- This situation is not related to spitting, it is a problem in a potential with reflection and transmission. Here the particle and antiparticle components feel opposite potentials and therefore have different transmission coefficients t and T.
- Represent axion as (1,1) and photon as (1, -1).
- Then axion = (1,1) after scattering goes to (t,T).
- (t,T)=a(1,1)+b(1,-1), a=(t+T)/2, b=(t-T)/2= amplitude for an axion converting into a photon
- For initial photon=(1,-1) we scatter to (t, -T)=c(1,1)+

d(1,-1), so we find that c= b=(t-T)/2, d= a=(t+T)/2. Notice the symmetries: amplitude of axion going to photon =

amplitude of photon going to axion and amplitude for photon staying photon = amplitude for an axion staying an axion.

First order scattering amplitudes for a particle in an external electromagnetic field is (Bjorken&Drell)

$$S_{\mathbf{p}'_+\mathbf{p}_+} = -\frac{ie}{(2\pi)^3}\int \frac{d^4y}{\sqrt{2\omega_{p_+}2\omega_{p'_+}}} e^{iq\cdot y}(p_+ + p'_+)_\mu A^\mu(y) = \frac{-ie(p_+ + p'_+)_\mu A^\mu(q)}{(2\pi)^3\sqrt{2\omega_{p_+}2\omega_{p'_+}}}$$

$$q^\mu = p'^\mu_+ - p^\mu_+$$

where $A^\mu(q) = \int d^4y e^{iq_\nu \cdot y^\nu} A^\mu(y)$

In our case the analog of the e x (zeroth component of 4- vector potential) is gB(y,z), no spatial components of 4-vector potential exist

- x independence of our potential ensures conservation of x component of momenta (that is, this is a two spatial dimensions problem)
- t independence ensures conservation of energy
- the amplitude for antiparticle has opposite sign, is -S
- Therefore an axion, i.e. the symmetric combination of particle antiparticle (1,1) goes under scattering to (1,1) +(S, -S), S being the expression given before. So the amplitude for axion going into photon (1,-1) is S, this agrees with a known result obtained by P. Sikivie many years ago for this type of external static magnetic field.

The “Classical” CM Trajectory

- If we look at the center of a wave packet, it satisfies a classical behavior (Ehrenfest). In this case we get two types of classical particles that have + or – charges.
- In the presence of an inhomogeneuos magnetic field, these two different charges get segregated.
- This can take place thermodynamically or through scattering (to see this effect clearly one should use here wave packets, not plane waves!).

Thermodynamic Splitting

- In the classical limit the particles have a kinetic energy and a potential energy gB
- The antiparticles have the same kinetic energy but a potential energy –gB
- The ratio of particles to antiparticle densities at a given point is given by the corresponding ratios of Boltzmann factors, that is   exp(-2gB(y,z)/kT).

Splitting through scattering

- From the expression of photon and axion in terms of particle and anti particle, we see that in the “classical” limit these two components move in different directions.
- If the direction of the initial beam is for example orthogonal to both the magnetic field and the direction of the gradient of the magnetic field, we obtain splitting of the particle and anti particle components
- There appears to be a radical difference between the case where spitting takes place, as opposed to the “frontal” case: in the splitting case, because the final momenta are different, the relative phases of particle and antiparticle grow even after we come out of interaction region.

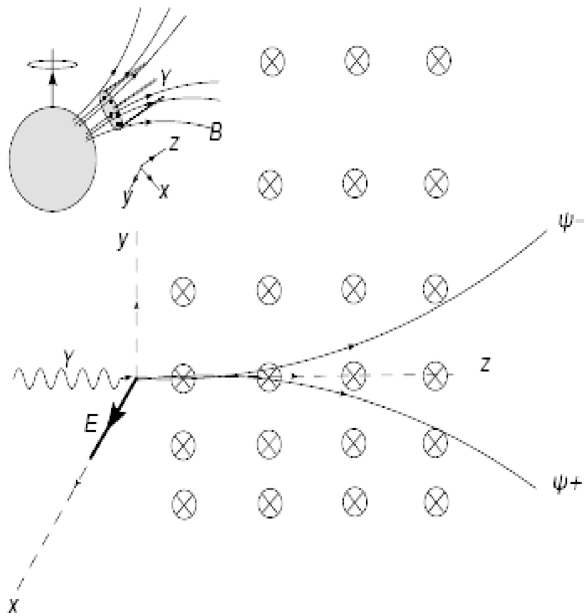
The Extreme Far Region

- In fact if we take the particle antiparticle splitting picture seriously, and consider even a very small splitting angle, in any case we can take the Extreme Far Region,
- In this limit the particle and antiparticle components will be separated, each of these components is 50% axion, 50% photon, so by going very far we get an effect of order 1!. New effect, not present in one dimensional experiments

Example of some Estimates

- Beam splitting, take distance between the beams of order de Broglie wave length, then for a magnetic field gradient of 1Tesla/cm, acting 10cm in the direction orthogonal to beam, we get splitting at L=1000,000km, for g close to upper bound from CAST.
- 1/L , -1/L are the momenta aquired
- Splitting represents O(1) effect, so what is obtained for smaller distances?. This is an interesting quantum mechanical scattering problem that has been studied, but not subject of this talk.

Cosmic Stern Gerlach experiment for ALPS



Eigenstates

The equation of motion for the photon-particle system takes the form (e.g., C09, Raffelt & Stodolsky 1988),[3]

$$\left[\mathbf{k}^2 - \omega^2 + \begin{vmatrix} m_\gamma^2 & -gB_\parallel\omega \\ -gB_\parallel\omega & m_a^2 \end{vmatrix}\right]\begin{pmatrix}\gamma \\ a\end{pmatrix} = 0, \qquad (3)$$

where ω is the photon energy and $B_\parallel$ the magnetic field in the direction of the photon polarization (the photon's E field). Clearly, neither pure photon nor pure ALP states are eigenstates of the system but rather some combination of them.

Let us now focus on the limit

$$|m_a^2 - m_\gamma(\omega)^2| \ll gB_\parallel\omega \sim 10^{-14} g_{-14} B_{16} \lambda_m^{-1}\,\mathrm{eV}^2 \qquad (4)$$

where $B_{16} = B_\parallel/10^{16}\,\mathrm{G}$, $g = 10^{-14} g_{-14}\,\mathrm{GeV}^{-1}$, and the photon wavelength, $\lambda = \lambda_m\,\mathrm{m}$. This condition is met either near resonance where $m_\gamma^2 \simeq m_a^2$ or when both masses are individually smaller than $\sqrt{gB_\parallel\omega}$ (which limit is actually met is irrelevant). The eigenstates of equation 3 are then given by

$$|\psi\rangle_- = [|\gamma\rangle + |a\rangle]/\sqrt{2}, \quad |\psi\rangle_+ = [|\gamma\rangle - |a\rangle]/\sqrt{2} \qquad (5)$$

where $|a\rangle$ is the axion state and $|\gamma\rangle$ is the photon state. The

Optics analogy

eigenvalues are $m_{\pm}^2 = \pm g B_{\parallel} \omega$. By analogy with optics, these masses are related to effective refractive indices: $n_{\pm} = 1 + \delta n_{\pm} \simeq 1 - m_{\pm}^2/2\omega^2$ (for $|\delta n_{\pm}| \ll 1$) meaning that different paths through a refractive medium would be taken by the rays. We note that there is no dependence on the particle or photon mass so long as equation 4 is satisfied.

In terms of the refractive index, the equation of motion for a ray may be found by minimizing the action $\int ds n(\mathrm{s})$. This is completely analogous to mechanics where we substitute $\mathfrak{L} \to \omega n_{\pm}$. In this case, a force is $\partial \mathfrak{L}/\partial \mathrm{s} = \pm(g/2)(\partial B/\partial \mathrm{s})$. Using our simplified geometry, depicted in figure 1, the momentum imparted on each state is

$$\delta p_y^{\pm} = \mp(g/2) \int dz \, (\partial B_x/\partial y) \tag{6}$$

where $B_x = B_x(y,z)$ (note that $dt = dz$ in the adopted units). Clearly, each of the beams will be affected in a similar way

[3] We work in natural units so that $\hbar = c = 1$.

Beam splitting from magnestar

In the limit $n_{\pm} \simeq 1$, the separation angle between the beams is

$$\theta \simeq 2p^{-1}|\delta p_y| \simeq \omega^{-1} g f_G B_{\parallel} \quad (7)$$

where p is the beam momentum along the propagation direction, i.e., the z-axis. This expression holds for small splitting angles and assumes relativistic axions. We also approximated $\int dz(\partial B_x/\partial y) = f_G B_{\parallel}$ where $f_G(N)$ is a geometrical factor depending on the magnetic field geometry, the inclination of our line-of-sight through the magnetized region (e.g., for pulsars and magnetars the magnetic field is predominantly dipolar and $f_G < 1$; see §3), and on the photon polarization. An

And its observable signature

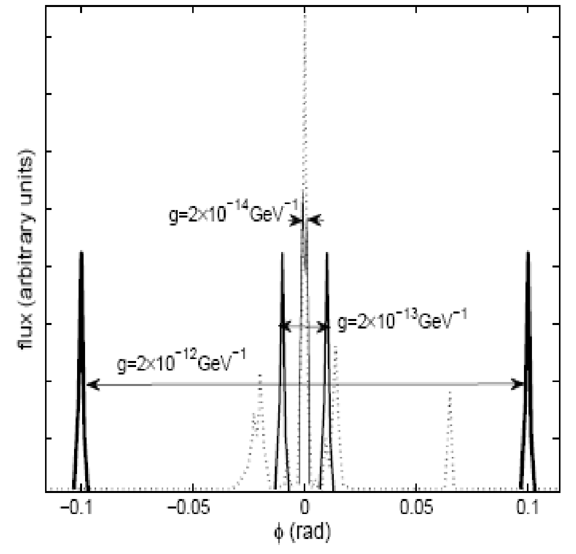


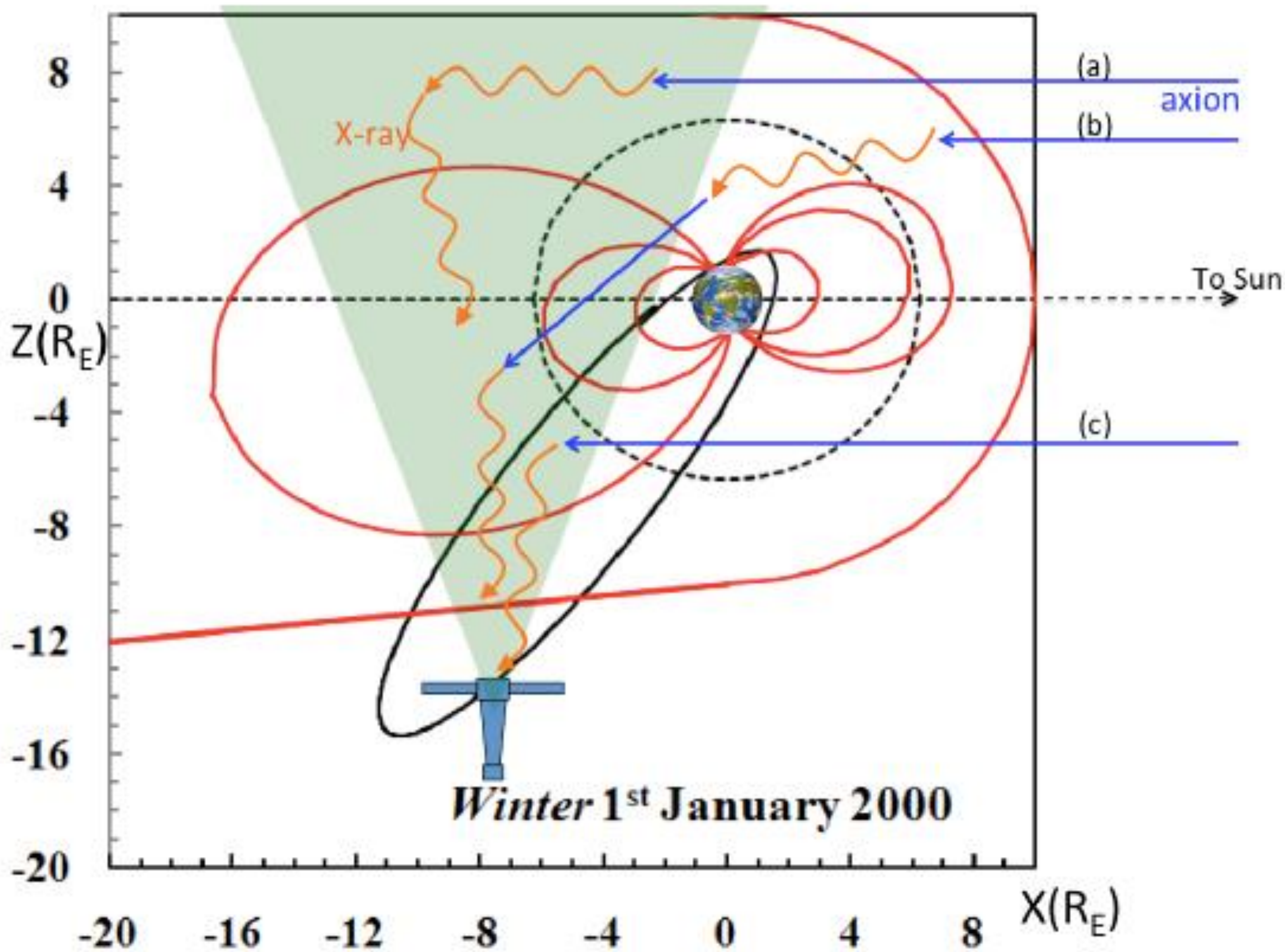
FIG. 2.— Splitting of the peak pulse at $\phi = 0$ rad in a single rotation light-curve of XTE J1810197 (dotted line; see Camilo et al. 2006) for several values of the coupling constant, g and assuming $\lambda = 1$ m, $f_G B_{||} = 10^{15}$ G. Note the similar fluxes of the split signals whose sum corresponds to that of the original pulse. Looking for the effects of pulse-splitting in the radio light-curves of magnetars allows one to be considerably more sensitive to light bosons compared to e.g., the CAST experiment and other astrophysical constraints. In particular, pulse splitting at meter wavelengths can be detected down to coupling constants $g_{\rm min} \gtrsim 10^{-14}$ GeV^{-1} for $m_a \ll 10^{-7}$ eV. Observing at longer wavelengths (and assuming all other parameters are fixed) will proportionally increase the sensitivity to lower values of $g_{\rm min}$ (see Eq. 8).

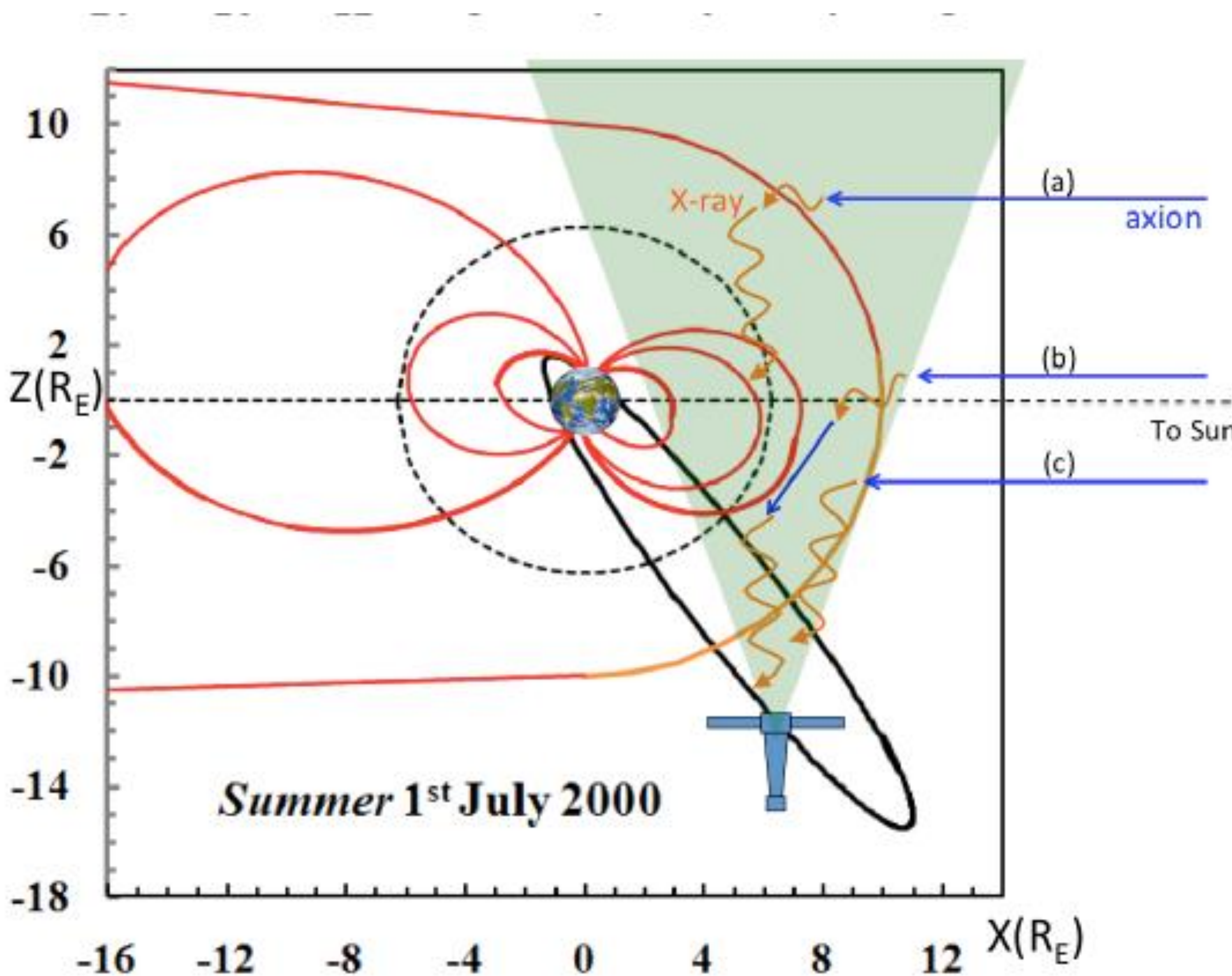
Sensibility for ALPS photon coupling

Assuming splitting angles $\theta \sim 10^{-2}\theta_{-2}$ rad are detectable at radio wavelengths (see §3), then the minimum coupling constant which can be probed, provided equation 4 holds, is

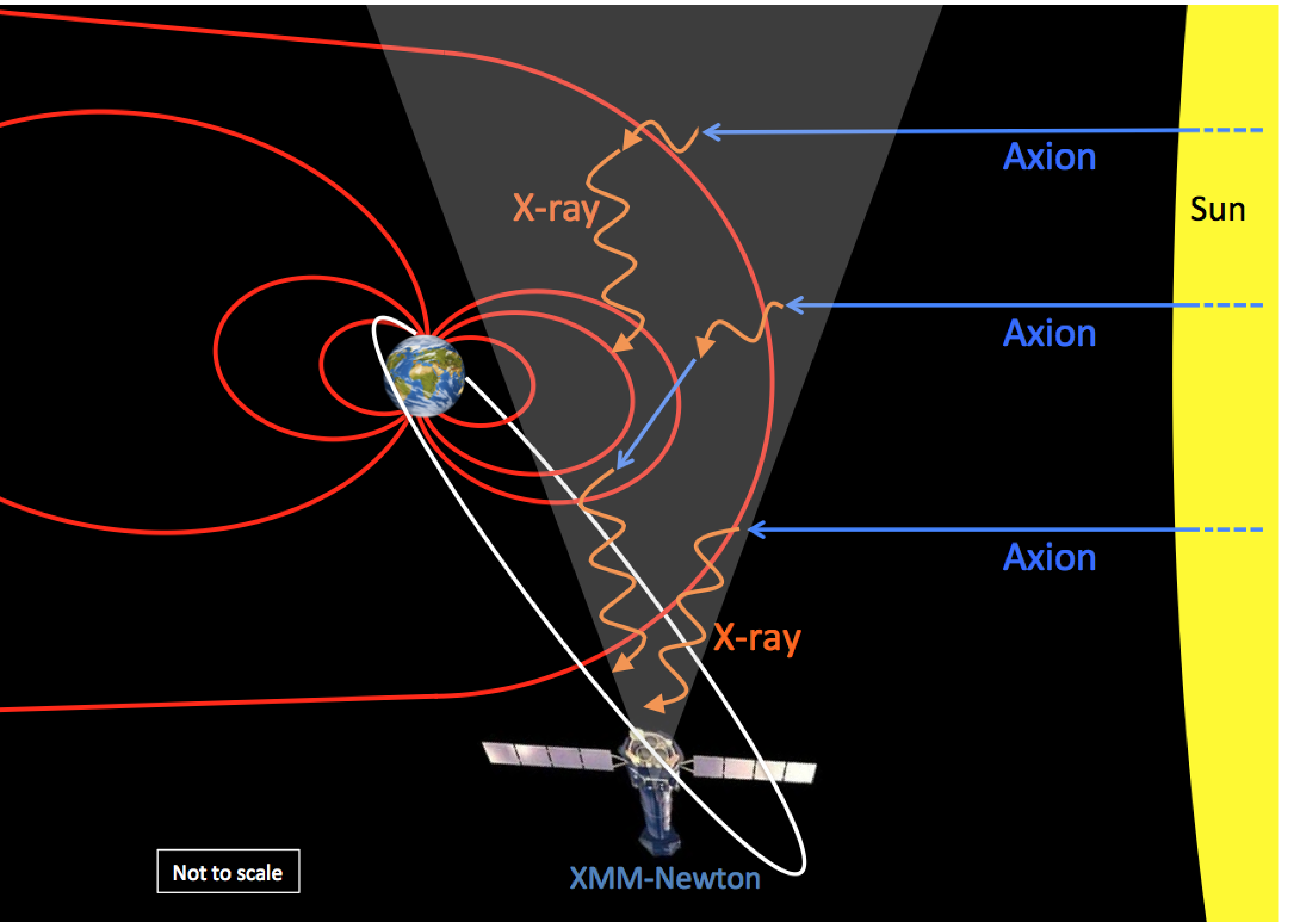
$$g_{\rm min} \sim 2 \times 10^{-14} \lambda_m^{-1} f_G^{-1} B_{16}^{-1} \theta_{-2}\, {\rm GeV}^{-1}. \qquad (8)$$

CLAIM OF AXIONS FROM THE SUN, FRASER ET. AL.





X-ray
(a)
axion
(b)
To Sun
(c)
Z(R_E)
X(R_E)
Summer 1st July 2000
10
6
2
-2
-6
-10
-14
-18
-16
-12
-8
-4
0
4
8
12



Axion
Axion
Axion
Sun
X-ray
X-ray
XMM-Newton
Not to scale

Frazer et al say (quoting) :

prompted by recent hints that the motion of axions and their conversion X-rays need not be perfectly co-linear in inhomogeneous magnetic fields (Guendelman 2008; Guendelman et al. 2010, 2012). These papers investigate the conversion probability *p* due to "axion splitting" in a number of ideal magnetic field geometries (infinitely thin solenoid, square well, Gaussian and δ-function) but not yet for the desired dipole approximation to the geomagnetic field.

However Fraser et. al. really go beyond what our calculations

can justify assuming the magnetic fields in space are smooth, the big scattering angles that they assume may be are a consequences of in-homogeneities at small scales of the magnetic fields that the axions from the sun. Fraser et. al. claim that assuming these almost isotropic angle distribution of the scattering, that this produce a very good fit with the data.

Historically there was a situation

where large scattering angles were observed, but the expectations, based on the favorite smooth models of the atom, predicted something very different, that was the discovery of Rutherford, are Fraser et. Al. up to something similar?

Conclusions concerning Part 1.

- Axion Photon interactions with an external magnetic field can be understood in terms of scalar QED notions.
- Standard, well known results corresponding to experiments that are running can be reproduced.
- Photon and Axion splitting in an external inhomogeneous magnetic field is obtained.
- By observing at large distances from interaction region, effect can be amplified.
- Stern Gerlach type splitting from magnestars is possible, giving high sensibility for ALPS photon coupling.
- New claims of AXIONS FROM THE SUN, where the phenomenon of beam splitting plays essential role

Potential solar axion signatures in X-ray observations with the XMM-Newton observatory

G.W. Fraser [1], A.M. Read [2*], S. Sembay [2], J.A. Carter [2] and E. Schyns [3]

Abstract

The soft X-ray flux produced by solar axions in the Earth's magnetic field is evaluated in the context of ESA's XMM-Newton observatory. Recent calculations of the scattering of axion-conversion X-rays suggest that the sunward magnetosphere could be an observable source of 0.2-10 keV photons. For XMM-Newton, any conversion X-ray intensity will be seasonally modulated by virtue of the changing visibility of the sunward magnetic field region. A simple model of the geomagnetic field is combined with the ephemeris of XMM-Newton to predict the seasonal variation of the conversion X-ray intensity. This model is compared with stacked XMM-Newton blank sky datasets from which point sources have been systematically removed. Remarkably, a seasonally varying X-ray background signal is observed. The EPIC count rates are in the ratio of their X-ray grasps, indicating a non-instrumental, external photon origin, with significances of 11σ (pn), 4σ (MOS1) and 5σ (MOS2). After examining the distribution of the constituent observations spatially, temporally and in terms of the accepted representation of the cosmic X-ray background, we conclude that this variable signal is consistent with the conversion of solar axions in the Earth's magnetic field, assuming the resultant photons are not strictly forward-directed, and enter the field-of-view of XMM-Newton. The spectrum is consistent with a solar axion spectrum dominated by bremsstrahlung- and Compton-like processes, distinct from a Primakoff spectrum, i.e. axion-electron coupling dominates over axion-photon coupling and the peak of the axion spectrum is below 1 keV. A value of 2.2×10^{-22} GeV^{-1} is derived for the product of the axion-photon and axion-electron coupling constants, for an axion mass in the μeV range. Comparisons, e.g., with limits derived from white dwarf cooling may not be applicable, as these refer to axions in the ~0.01 eV range. Preliminary results are given of a search for axion-conversion X-ray lines, in particular the predicted narrow features due to silicon, sulphur and iron in the solar core, and the 14.4 keV transition line from ^{57}Fe.

Part 2. Consider now the Axion external Fields case

To give an example of tachyonic mass generation for a gauge field due to the presence of a coherent axion field, consider the lagrangian L, which photons and their coupling to axions (or photons coupling to π^0 mesons for a different value of the coupling constant λ).

$$L = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \frac{\lambda}{8} \phi F_{\mu\nu} F_{\alpha\beta} \varepsilon^{\mu\nu\alpha\beta} \qquad (2.1)$$

The lagrangian (2.1) can be written as[(1),(2)]

$$L = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{\lambda}{4} (\partial_\beta \phi) F_{\mu\nu} A_\alpha \varepsilon^{\mu\nu\alpha\beta} \qquad (2.2)$$

tachyonic instability. Explicitly, the equations of motion derived from (2.2) are:

$$\partial_\rho F^{\rho\sigma} + (\lambda a/2)\, \varepsilon^{\rho\beta\sigma 0} F_{\rho\beta} = 0 \tag{2.3}$$

Defining then the magnetic field B^i, through the equation

$$B^i = \frac{1}{2}\, \varepsilon^{ijk0} F_{jk} \tag{2.4}$$

In terms of this auxiliary field B^i, equation (2.3) can be writen as

$$\varepsilon^{jik0}\, \partial_i B_j + \lambda a\, B^k = - \partial_0 F^{0k} \tag{2.5}$$

multiplying both sides by $[\varepsilon_{lmk0}\, \partial^m - (\lambda a) g_{lk}]$, one obtains

$$\{ \partial_\mu \partial^\mu - (\lambda a)^2 \} B_k = (\lambda a)\, \partial^0 F_{0k} \tag{2.6}$$

in the gauge $A^0 = 0$, $\partial^0 F_{0k} = (\partial^0)^2 A_k$. It is easy to see then, that if in momentum space we can choose a basis where $B^k = \zeta A^k$, then a simple dispersion relation is obtained from (2.6). For plane waves with wave number vector **k**, we obtain the eigenvalues $\zeta = \pm(\mathbf{k}^2)^{1/2}$, 0. The $\pm(\mathbf{k}^2)^{1/2}$ eigenvalues are obtained for right or left handed polarizations (therefore with a phase difference of $\pm\pi/2$ between the cartesian components) vectors perpendicular to **k**. The value $\zeta = 0$ is unphysical, since it corresponds to a polarization parallel to **k** and from (2.6), with $k^0 = 0$, i.e. a pure gauge configuration.

Inserting $B^k = \zeta A^k$ into (2.6), with the values $\zeta = \pm(\mathbf{k}^2)^{1/2}$, we get the following dispersion relations:

$$(k^0)^2 = (\mathbf{k}^2)^{1/2} [(\mathbf{k}^2)^{1/2} - \lambda a] \qquad (2.7a)$$

$$(k^0)^2 = (\mathbf{k}^2)^{1/2} [(\mathbf{k}^2)^{1/2} + \lambda a] \qquad (2.7b)$$

For the mode (2.7a), we see that k^0 becomes imaginary for $|\mathbf{k}| < \lambda a$, revealing a dynamic instability of the system. Furthermore, we see that $k^0 = 0$ is achieved not only for $\mathbf{k} = 0$, but according to (2.7a), also for $|\mathbf{k}| = \lambda a$, and this is a manifestation of the "tachyonic" nature of the instability.

Relation to baryogenesis

In the case of interest, we want to introduce a chemical potential for B+L, where the baryon current b^μ and the lepton current l^μ satisfy:

$$2\partial_\mu b^\mu = 2\partial_\mu l^\mu = \partial_\mu (b^\mu + l^\mu) \\ = 2n_f(32\pi^2)^{-1}\{-2g^2 F^a_{\mu\nu} F^a_{\alpha\beta}\, \varepsilon^{\mu\nu\alpha\beta} + g'^2 F'_{\mu\nu} F'_{\alpha\beta}\, \varepsilon^{\mu\nu\alpha\beta}\} \qquad (3.1)$$

Here $F^a_{\mu\nu}$ and $F'_{\mu\nu}$ are the gauge field tensors for the $SU(2)_L$ and U(1) gauge fields of the standard electroweak interactions, g and g' being the corresponding coupling constants and n_f being the number of generations.

Since $F'_{\mu\nu} F'_{\alpha\beta}\, \varepsilon^{\mu\nu\alpha\beta} = 2\partial_\beta(F'_{\mu\nu} A'_\alpha\, \varepsilon^{\mu\nu\alpha\beta})$, we get that a chemical potential μ for B+L leads to a mass term

$$- \mu n_f(4\pi^2)^{-1} g'^2 \,(F'_{\mu\nu} A'_\alpha\, \varepsilon^{\mu\nu\alpha 0}) \qquad (3.2)$$

for the U(1) gauge fields. As mentioned before, we ignore the mass generation in the non abelian sector, because there parity invariant magnetic mass generation is expected to overcome the above mentioned effect. Also parity conserving magnetic mass generation takes place in the cancelled by (3.2) originated by a net density of B+L. That is, if

$$\mu n_f (4\pi^2)^{-1} g'^2 = (\lambda/4)\, \partial_t\phi$$

i.e. if $\mu = \lambda\, (n_f g'^2/\pi^2)^{-1}\, \partial_t\phi$, $\lambda \sim n_f g'^2/(8\pi^2 f_a)$ up to factors of order 1 that depend on the specific axion model. Here f_a is the scale of the symmetry

$N_f - N_{af} \sim 6^{-1} g_f\, \mu T^2 \sim (48 f_a)^{-1} g_f (\partial_t\phi) T^2$, where g_f is the number of fermion species. Since B-L = 0 in a scenario where we start from B = L = 0 at some high temperature and where only B+L is generated by sphaleron effects. Then $B = 2^{-1}F \sim (96 f_a)^{-1} g_f (\partial_t\phi) T^2$. It is convenient to calculate a quantity that remained invariant since the decoupling of B+L violating effects and up to now (assuming there were no significant entropy producing phase transitions since then), which is the ratio B/s, where s is the entropy density. Since $s = (45)^{-1}(2\pi^2 g_* T^3)$, where g_* = effective number of degrees of freedom, this gives

$$B/s \sim [4\pi^2 g_* T f_a]^{-1} g_f (\partial_t\phi)$$

Mass generation from space-like axion background

- Considering both the effect of an explicit mass term for the photon, axion-photon coupling and a space-like dependent external field of the form

$$a(x) = \zeta x_1$$

We obtain 3 different dispersion

relations for 3 diferent polarizations

the corresponding dispersion relations are

$$\begin{cases} k_{1L}^{CS} = k_1^0 = \sqrt{\omega^2 - m^2 - k_\perp^2}; \\ k_{1+}^{CS} = \sqrt{\omega^2 - m^2 - k_\perp^2 - \zeta_x \sqrt{\omega^2 - k_\perp^2}}; \\ k_{1-}^{CS} = \sqrt{\omega^2 - m^2 - k_\perp^2 + \zeta_x \sqrt{\omega^2 - k_\perp^2}}, \end{cases}$$

Representing anisotropic mass generation, the generation of

space dependent axion, or pion field has been considered in nuclear collisions and near the surface of neutron stars has been considered by different authors, for example.

Recently the effect of such pseudoscalar condensation on the cooling of neutron stars has been considered.

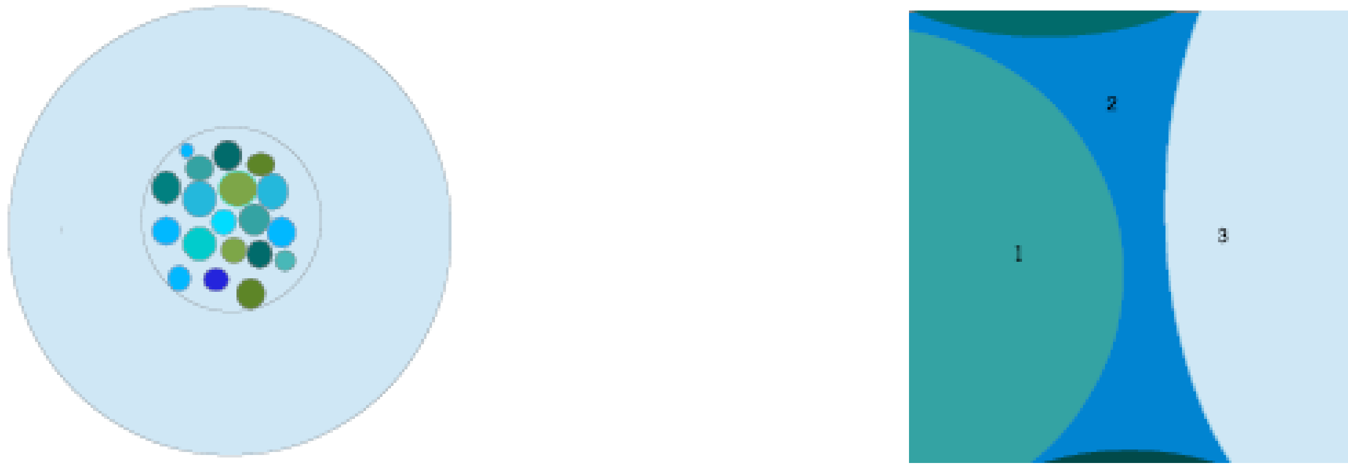


Figure 1: A sketch of possible domains with pseudoscalar condensates inside a neutron star

a changes linearly from a_- to a_+ across the gap. Then inside region 2 the relevant pseudoscalar background can be locally described by

$$a(x) = \zeta_\lambda x^\lambda [\theta(\zeta \cdot (x - x_-)) - \theta(\zeta \cdot (x - x_+))] \tag{2}$$

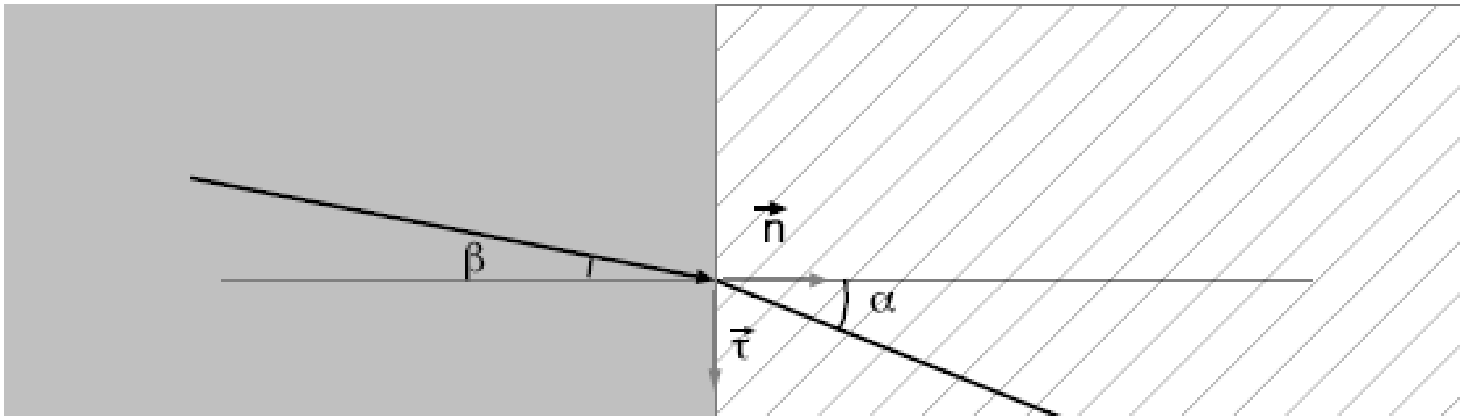


Figure 2: The geometry of photon propagation. $\vec{n}$ is a normal vector. In the left region (region 1) the pseudoscalar condensate takes a constant value. Region 2 (right) is assumed to be described by MCS electrodynamics describing a varying pseudoscalar condensate as befits a transition region

4 Escaping from the boundary layer

After escaping the first region photons appear, if they are not reflected, in the intermediate shell where MCS electrodynamics is at work. To leave this medium and gain access to another domain where $a =$ constant (possibly zero) photons have to pass through one more boundary. This corresponds to the boundary between regions 2 and 3 in Fig. 1.

effect of two boundaries of the domain. One may see that the effect is substantial: the total luminosity decreases by 10 times. Of course, we are speaking only about small regions inside the star. The effect on the *total* rate of cooling should not be so dramatic. In fact its precise magnitude does depend on many parameters that we do not and are of astrophysical nature such as the size, distribution and number of domains, magnitude of gradients in the intermediate shells. However the existence of parity breaking areas in the inner layers of star should slow down the cooling for sure.

5 Photon decay

Now let us discuss another phenomena, which may give contribution to the flux of outgoing particles, namely, the possibility of photon decay in a volume where $a \neq$ constant. For neutron stars the importance of this phenomenon is probably small but it is interesting on its own nevertheless.

effect of the photon decaying. The total decay width for high-energy positive polarization in a linearly varying pseudoscalar background is

$$\Gamma_+ \simeq \frac{\alpha\zeta}{3}$$

Some References, part 1

- **Continuous axion photon duality and its consequences.**E.I. Guendelman **Mod.Phys.Lett.A23:191-196,2008, arXiv:0711.3685** [hep-th]

- **Localized Axion Photon States in a Strong Magnetic Field.** E.I. Guendelman **Phys.Lett.B662:227-230,2008**, **arXiv:0801.0503** [hep-th]
- **Photon and Axion Splitting in an Inhomogeneous Magnetic Field.** E.I. Guendelman **Phys.Lett.B662:445,2008, arXiv:0802.0311** [hep-th]

- **Cosmic Analogues of the Stern-Gerlach Experiment and the Detection of Light Bosons.**Doron Chelouche, Eduardo I. Guendelman , **Astrophys.J.699:L5-L8,2009**. **arXiv:0810.3002** [astro-ph]

- **Photon Production From The Scattering of Axions Out of a Solenoidal Magnetic Field.** Eduardo I. Guendelman, Idan Shilon,, Giovanni Cantatore,, Konstantin Zioutas, **JCAP 1006:031,2010, arXiv:0906.2537** [hep-ph]

Potential solar axion signatures in X-ray observations with the XMM-Newton observatory

G.W. Fraser [1], A.M. Read [2*], S. Sembay [2], J.A. Carter [2] and E. Schyns [3]

References concerning Part 2

- 1. Published in Phys. Lett. B

WIS-91/53 Ph Aug

Axion Driven Baryogenesis

E.I.Guendelman

Department of Nuclear Physics,
Weizmann Institute of Science,
Rehovot 76100, Israel

and

D.A.Owen

Department of Physics,
Ben Gurion University of the Negev,
Beer Sheva 84105, Israel

Time dependent axion as a mechanism of Lorentz violation

2. S. M. Carroll, G. B. Field, R. Jackiw, Phys. Rev. D **41**, 1231 (1990).

3. Anisotropic mass generation from space dependent external axion field and use for possible effects in heavy nuclear collissions

E.I.Guendelman and D.A.Owen, Phys. Lett. **251B**, 439 (1990).
E.I.Guendelman and D.A.Owen, Phys. Lett. **252B**, 113 (1990).

4. Anomalous positron excess from Lorentz violating QED

A,A, Adrianov, Q, Espiru, P. Giacconi, R. Soldati, ArXiv: 0907.3709

5.

Effects of pseudoscalar condensation on the cooling of neutron stars

A. A. Andrianov[1,2], D. Espriu[2] and S. S. Kolevatov [1]