# Hunting axions in low Earth orbit

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We show that an x-ray observatory in low Earth orbit can, in principle, detect solar axion emission exploiting the same physics as experiments like CAST. We call this effect GECOSAX. The obtainable sensitivity strongly depends on the chosen orbit and time of year the observation is performed. We included the effects of the detailed geomagnetic field shape, precise orbit computation and the Earth atmosphere. Our background model is based on actual observations performed by the SUZAKU satellite. The final, limiting sensitivities we obtain for a realistic mission are at $2\,\sigma$: $g_{a\gamma} < (4.7-6.6)\times 10^{-11}\,\mathrm{GeV}^{-1}$, for axion masses $m_a < 10^{-4}\,\mathrm{eV}$, which significantly exceeds current laboratory sensitivities.

## 1 Introduction

The basic concept for the detection of solar axions was described by P. Sikivie in a seminal paper [1] in 1983. This very same technique is still employed today; the most recent incarnation being the CAST experiment [2]. The detection rate in these experiments is proportional to the conversion probability, which in the limit $m_a \to 0$ is given by

$$P^s_{a\gamma} = 2.45 \times 10^{-21} \left(\frac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)^2 \left(\frac{B}{\mathrm{T}}\right)^2 \left(\frac{L}{\mathrm{m}}\right)^2 . \qquad (1)$$

$P^s_{a\gamma}$ depends only on the product of $(B \cdot L)^2$, thus any experiments having similar values of $(B \cdot L)^2$ will have a similar conversion rate. The signal consists of x-ray photons in the energy range $2-10\,\mathrm{keV}$. As a reference value we can use the CAST values for $B \simeq 9\,\mathrm{T}$ and $L \simeq 10\,\mathrm{m}$, which yields $(B \cdot L)^2 \simeq 8000\,\mathrm{T}^2\mathrm{m}^2$. The basic idea of geomagnetic conversion of solar axions (GECOSAX), is to replace the strong but small magnet of CAST by the weak but large magnet, called Earth [3]. For the Earth, we have $B \sim 3 \cdot 10^{-5}\,\mathrm{T}$ and $L \sim 600\,\mathrm{km}$ and as a result $(B \cdot L)^2 \simeq 300\,\mathrm{T}^2\mathrm{m}^2$. This value is only about one order of magnitude smaller than the one of CAST, which *e.g.* could be compensated by a larger x-ray collection area. The obvious challenge for the GECOSAX approach is given by the x-ray emission directly from the Sun, which exceeds the GECOSAX signal by about 13 orders of magnitude. Here, following observation can be exploited: solar x-rays will be completely absorbed by the Earth or its atmosphere, whereas solar axion can pass it unattenuated. Therefore, on the night side of the Earth there will be solar axions but *no* solar x-rays. Thus, a GECOSAX experiment is indeed very similar to a terrestial experiment. In this contribution, we will explore the relevant effects, which need to be included for reliable computation of the expected GECOSAX signal. We also, will present a background estimate based on data of the SUZAKU satellite. Combined, this will allow us to arrive at a sensitivity to $g_{a\gamma}$ for such an experiment. A more detailed version of the material presented here can be found in Ref. [4].

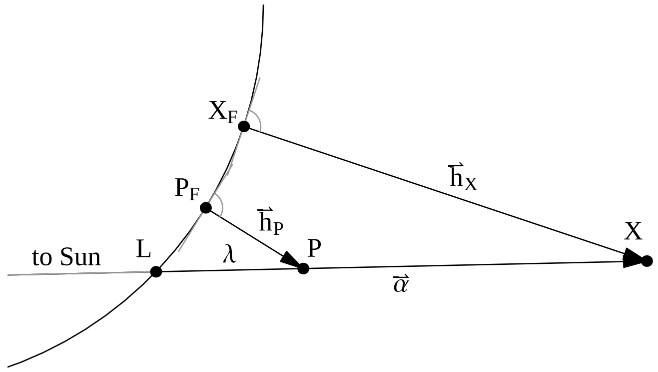


Figure 1: Geometry of the GECOSAX configuration drawn in the plane spanned by the center of the Earth, the center of the Sun and the satellite's position at $t_0$. Figure taken from [4].

## 2 Geometry & satellite position

The geometry of the GECOSAX configuration is depicted in Fig. 1, where $X$ denotes the position of the satellite at $t_0$. The altitude of the satellite is then given by $\left|\vec{h}_X\right|$. Here, $\vec{\alpha} = \overline{LX}$ is the so called line of sight (LOS). The actual axion conversion will take place along the LOS, thus the axion conversion path length is given by $|\vec{\alpha}|$. Note, that $|\vec{\alpha}| \geq \left|\vec{h}_X\right|$, thus the altitude of the satellite is a lower bound on the available axion conversion path length. In order to to compute $P_{a\gamma}$ it is necessary to compute the position of the satellite, the Earth and the Sun relative to each other for a given time $t_0$. This is accomplished by using simple but accurate algorithms for the ephemeris of the Sun. The satellite's position is obtained from an analytic perturbation theory, which was developed to allow efficient tracking of a large number of objects in low Earth orbit on the very limited computers of the 60's. The algorithm we use yields errors of about 10 km, which are negligible for our purposes. Another advantage of this algorithm is that initial conditions for many satellites are easily available. In an actual satellite mission, the errors in the position of the satellite will be orders of magnitude smaller.

## 3 Magnetic field & Earth atmosphere

The magnetic field of the Earth is a complex and interesting system and its study is a whole field of research on its own. It is far from being a simple dipole field and its symmetry axis is not aligned with the rotation axis of the Earth, which leads to a diurnal modulation by the rotation of the Earth. Fortunately, for our purposes we only need to know the direction and magnitude of the $\vec{B}$-field along the LOS. This information is extracted from a global magnetic model which is based on ground and space observations of the magnetic field over an extended period of time. This data is then used to determine the coefficients of an expansion in spherical harmonics. Knowing these coefficients it is straightforward to retrieve the direction and magnitude of the $\vec{B}$-field. The field model we employ is accurate up to altitudes of about 1000 km and therefore, we will restrict our analysis to this range.

The effect of the Earth atmosphere on the propagation of x-rays is two-fold: First, there is refraction, which will create an effective mass $m_\gamma$ for the photon. $m_\gamma$ plays a crucial role in matching the momenta of the axion and the photon and therefore, has a strong effect on $P_{a\gamma}$. Secondly, there is absorption, which limits photon propagation to about one scattering length $\tau$. Both effects scale with the air density $\rho$, which itself is a function of altitude $h$. The effects scale with density like $m_\gamma \propto \rho(h)^{\frac{1}{2}}$ and $\tau \propto \rho(h)^{-1}$. The proportionality constants are well know from laboratory experiments. Given $\rho(h)$ it is then straightforward to include both, the effect from refraction and absorption, into the computation of $P_{a\gamma}$. The density profile of the atmosphere follows a simple barometric height formula $\rho(h) \propto \exp h/h_0$ only up to $h \leq 50\,\mathrm{km}$. Beyond that, various other effects like diffusion or local heating by solar UV radiation, interaction of partially ionized air with the magnetic field *etc.* become important. There are various semi-empirical models available to describe the rich dynamics of the upper Earth atmosphere. Using a state of the art model we found that the total density variations encountered are insignificant for altitudes above $h > 70\,\mathrm{km}$ which determine the axion-photon conversion rate. Therefore, we use a static, average atmosphere which is approximated by an exponential of a higher order polynomial in $h$. This, greatly simplifies the treatment of atmospheric effects. Absorption is important up to altitudes of about 80 km, whereas refraction can not be neglected up about $h \simeq 120\,\mathrm{km}$.

# 4 Orbit choice

All the ingredients are then combined to computate $P_{a\gamma}$. As a result, the expected signal strength along each point of the orbit of a given satellite can be predicted with an error of about 10%. Clearly, orbits which provide the maximal signal strength are preferable over those ones which only yield a low signal strength. In any real experiment there will be background as well and thus the appropriate measure of signal strength is significance $S$, defined like this

$$S = \underbrace{A^{1/2} F^{-1/2}}_{=:Q} \underbrace{t^{1/2} \Phi_{10}}_{=:\Sigma} = Q\Sigma\,, \tag{2}$$

with $A$ being the effective x-ray collection area, $F$ the background rate integrated over the relevant energy range and source size. $t$ is the available observation time, which is a sensitive function of the chosen orbit, since only those parts of the orbit in the Earth shadow count towards $t$. Here, $\Phi_{10}$ is the appropriately averaged flux of GECOSAX photons for $g_{a\gamma} = 10^{-10}\,\mathrm{GeV}^{-1}$. Note, that $\Sigma$ depends only on the chosen satellite orbit, whereas $Q$ depends only on the instrument used for x-ray observation. Thus, we can look for the best possible orbit without actually having to specify the instrument. On a typical orbit, the available conversion path length or length of the LOS will be largest at the entry and exit points of the Earth shadow for purely geometric reasons. Thus, the GECOSAX signal will be largest there as well. However, depending on the type of instrument aboard the satellite the observation cannot start at the point of entry and last till the point of exit. Therefore, we have to distinguish two types of missions: fixed mode missions, which can use the full duration of the dark orbit and turning mode missions, which have to discard the first and last 10 minutes of each dark orbit. Instead of designing an optimal orbit we chose to survey orbits of existing satellites and to identify the most suitable ones for the observation of GECOSAX. Naively, one would expect that high altitudes, to maximize the axion conversion path, with a high inclination, which carries the satellites over the magnetic poles, which have the highest $\vec{B}$-field, would be optimal. This expectation is well corroborated by our survey of 50 orbits with altitudes below 1000 km.

## 5 Sensitivity to $g_{a\gamma}$

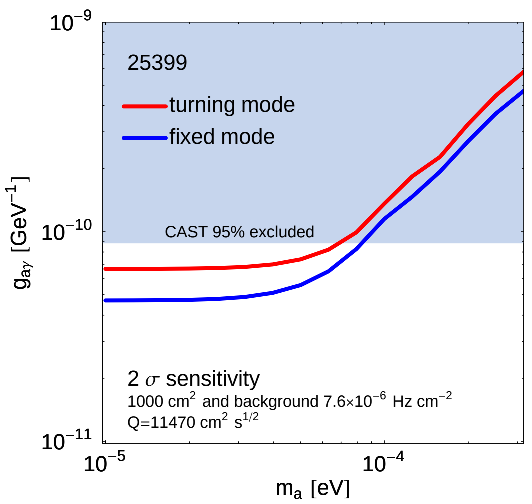


Figure 2: Sensitivity to $g_{a\gamma}$ as a function of the axion mass $m_a$ at $2\,\sigma$ (95%) confidence level. The blue shaded region is excluded by the CAST experiment [2]. Figure taken from [4].

Using the optimal orbit, identified in the previous section, we now can compute the expected limiting sensitivity for an instrument of given size and background level. The background level, we assume corresponds to the one measured by the XIS FI sensor aboard the SUZAKU satellite [5]. The effective x-ray collection area is taken to be $1000\,\text{cm}^2$ which is well within the range of currently in space used x-ray optical systems. The resulting sensitivity limit to $g_{a\gamma}$ as a function of the axion mass $m_a$ is shown in Fig. 2. The number given in the left hand upper corner of this figure, is the US SPACECOM ID number of the satellite used. This orbit is nearly circular and has an average altitude of about 820 km and an inclination with the respect to the equator of 82°. Obviously, the fixed mode observation provides better sensitivity since it can use more observation time, which in addition has a higher signal strength. For $m_a < 2\cdot 10^{-5}\,\text{eV}$ the sensitivity limit from a realistic, currently feasible mission is $4.6\cdot 10^{-11}\,\text{GeV}^{-1}$. If one would envisage larger detectors and a dedicated mission limits of the order $(2-3)\cdot 10^{-11}\,\text{GeV}^{-1}$ may be achievable.

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