Detecting solar axions using Earth's magnetic field

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We have recently shown that Geomagnetic Conversion of Solar Axions to X-rays (GECOSAX), can yield a photon flux with average energy $\langle\omega\rangle \simeq 4\,\text{keV}$, which is measurable by an orbiting detector on the dark side of the Earth (1). A key ingredient of our proposal is to use the Earth as an x-ray shield and look for axions coming through the Earth on the night side. This effectively removes the solar x-ray background; see Fig. 1 for a schematic representation of this setup. In what follows, we will explain how the recent measurements of the dark-Earth x-ray background by the Suzaku satellite demonstrate the feasibility of our proposal.

The radius of the Earth is $R_\oplus \approx 6.4 \times 10^3\,\text{km}$ and its magnetic field is well approximated by a dipole for distances less than 1000 km above the surface. The field strength is $B_\oplus \simeq 3 \times 10^{-5}\,\text{T}$ at the equator and it drops as $1/r^3$ (2). However, over distances $L \ll R_\oplus$ above the Earth, we may assume $B_\oplus = const$. As we are interested in low Earth orbits, $L < 1000\,\text{km}$ (1) and this is a valid assumption. We ignore the atmosphere of the Earth in our treatment, since for $L > 150$ km, solar axions essentially travel in vacuum.

For an axion mass $m_a \leq 10^{-4}\,\text{eV}$, $\omega = 4\,\text{keV}$, and an orbit of $L_\oplus \simeq 600\,\text{km}$, the axion to photon conversion probability can be approximated as

$$p_\gamma(L) = \frac{1}{4}\left(g_{a\gamma} B L\right)^2 \,, \tag{1}$$

where $g_{a\gamma}$ is the coupling of the axion to the photon and has dimension $(\text{Energy})^{-1}$, in units where $\hbar = c = 1$. The spectrum of solar axion flux at Earth is given by (4; 3)

$$\frac{d\Phi_a}{dE_a} = 3.821 \times 10^{10} \left(\frac{g_{a\gamma}}{10^{-10}\,\text{GeV}^{-1}}\right)^2 \frac{(E_a/\text{keV})^3}{e^{E_a/1.103\,\text{keV}} - 1}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{keV}^{-1}, \tag{2}$$

where E_a is the solar axion energy and $\langle E_a \rangle = 4.2$ keV. To compare with available data, we integrate the above spectrum over 2-7 keV to find the solar axion flux at Earth:

$$\Phi_a = 2.7 \times 10^{11} (g_{a\gamma}/10^{-10}\,\mathrm{GeV}^{-1})^2\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}, \tag{3}$$

Thus, for $g_{a\gamma} = 10^{-10}\,\mathrm{GeV}^{-1}$ and $B = B_\oplus$, the expected flux of x-rays at an altitude of $L_\oplus$ near the equator is

$$\Phi_\gamma(L_\oplus) \equiv \Phi_a\, p_\gamma(L_\oplus) \approx 3 \times 10^{-7}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}. \tag{4}$$

In Ref. (1), based on the published technical specifications of the 'Rossi x-ray timing explorer' (RXTE) (5), we had estimated that the above flux is measurable above background, on the dark side of the Earth. However, recently the Suzaku x-ray satellite team has measured the dark-Earth x-ray background in the range of 2-7 keV, for calibration purposes (6). This satellite has a circular orbit of 575 km with a 33° inclination. The Suzaku telescope does not have a fast slew rate and cannot perform our proposed measurements. However, as will be shown below, a telescope capable of tracking the solar core on the dark side of the Earth and with similar x-ray detection capabilities will be sensitive to axion-photon couplings far below the current bounds.

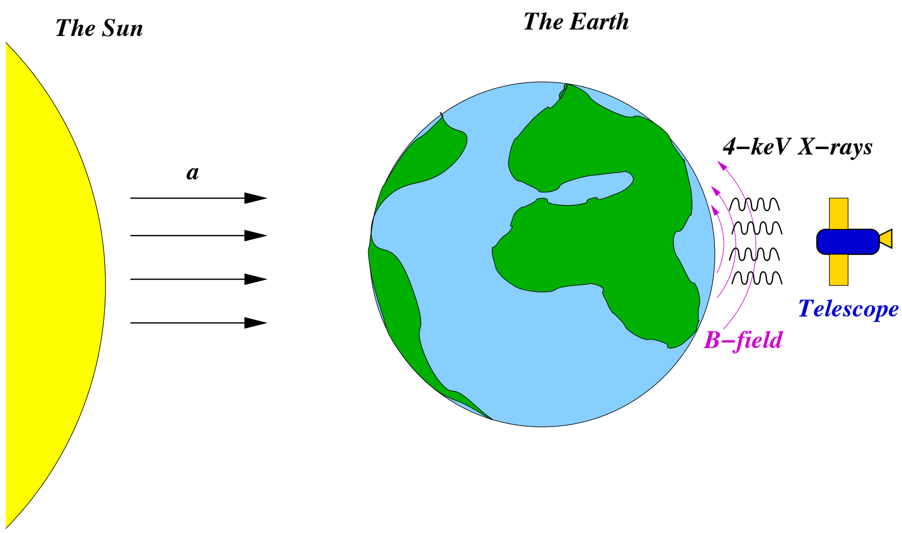

Fig. 1. The observational setup, using GECOSAX.

The effective area of detection used in the Suzaku measurement is about 300 cm^2 in the 2-7 keV range (6). The dark Earth background per unit area is presented in Fig. (2) (7). Given the above effective area, the $1'$ resolution of the x-ray telescope, and the Suzaku dark Earth data, we conclude that our proposed measurement of the x-ray flux from solar axion conversion is clearly feasible. The Suzaku team estimates that with 3×10^5 s of data, a 4σ bound $g_{a\gamma} < 10^{-10}$ GeV^{-1} would have been possible (6).

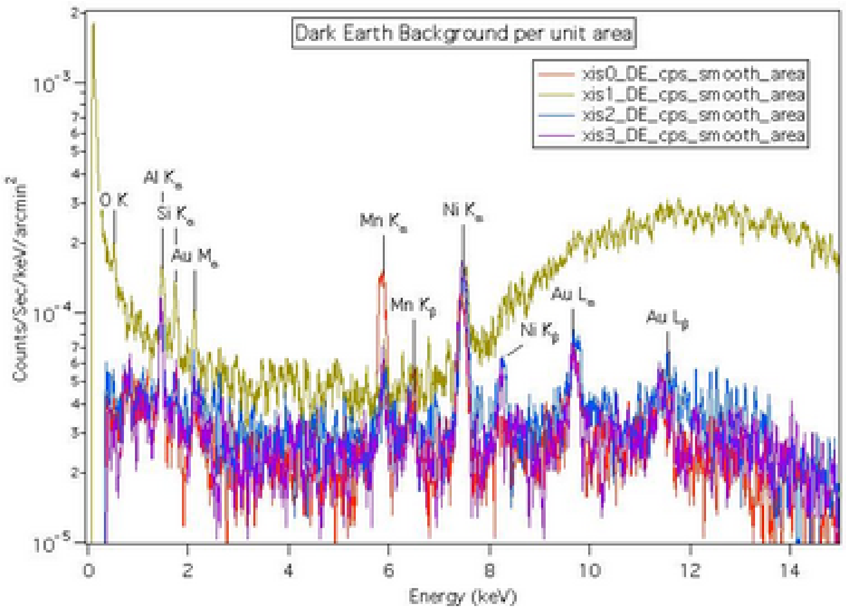

Fig. 2. Dark-Earth background measured by Suzaku (courtesy of the Suzaku team) (7).

Based on the Suzaku data (6), we have plotted the discovery reach of a solar-core-tracking x-ray telescope, as a function of m_a, in Fig. (3).

The signal has distinct features, providing for a definitive discovery. These features are: *(1) X-rays with a thermal energy distribution peaked at approximately* 4 keV, *on the night side of the Earth. (2) These x-rays would only come from the center of the Sun, which subtends approximately* $3'$ *on the sky. (3) There would be an orbital variation with magnetic field strength and orientation, as well as an annual modulation by the Sun-Earth distance.* Here we add that the Earth-occulted background can be measured *in situ*, by pointing the x-ray telescope away from the direction of the core of the Sun.

We note that the observation of our signal amounts to viewing an x-ray image of the solar core through the Earth! Therefore, our method can achieve an unambiguous detection of solar axions. We conclude that, for solar axions with $m_a < 10^{-4}$ eV, an orbiting x-ray telescope, with an effective area in the few$\times 10^3$ cm^2 range, can probe solar axion $g_{a\gamma}$, well beyond the reach of current laboratory experiments.

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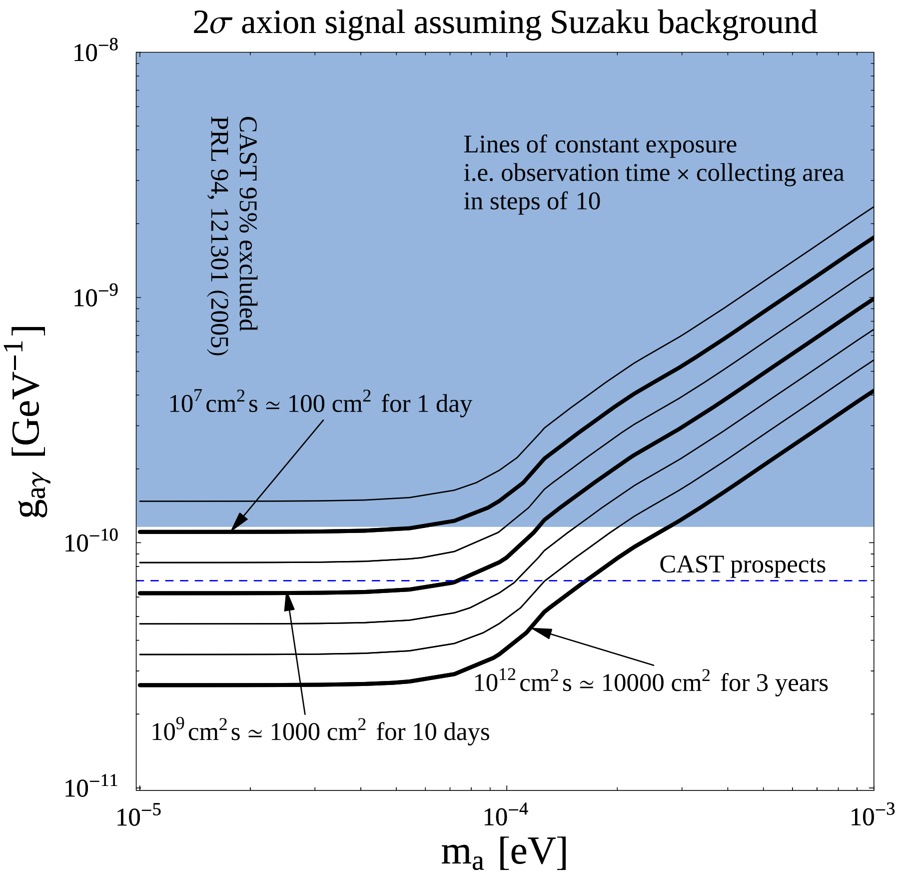

Fig. 3. The shaded area schematically depicts the CAST 95% C.L. excluded region (3). The lines show sensitivities obtainable with the background measured by Suzaku.

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