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X-Ray Searches for Solar Axions

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Abstract. Axions generated thermally in the solar core can convert nearly directly to X-rays as they pass through the solar atmosphere via interaction with the magnetic field. The result of this conversion process would be a diffuse centrally-concentrated source of few-keV X-rays at disk center; it would have a known dimension, of order 10% of the solar diameter, and a spectral distribution resembling the blackbody spectrum of the solar core. Its spatial structure in detail would depend on the distribution of mass and field in the solar atmosphere. The brightness of the source depends upon these factors as well as the unknown coupling constant and the unknown mass of the axion; this particle is hypothetical and no firm evidence for its existence has been found yet. We describe the solar magnetic environment as an axion/photon converter and discuss the upper limits obtained by existing and dedicated observations from three solar X-ray observatories: *Yohkoh*, RHESSI, and *Hinode*.

1. Introduction

The axion is a hypothetical weakly-interacting particle whose existence would solve certain problems in particle physics. There are also many implications for astrophysics, as described compendiously by Raffelt (1996) and summarized more recently by Raffelt (2007) and Zioutas et al. (2009). From the solar perspective these implications are not trivial; a substantial part of the solar core energy production (of order 0.1%) could be carried by these particles, if they existed (Gondolo & Raffelt 2009). Because they are weakly interacting, their emission by the core comprises an additional channel for solar energy loss, as do the neutrinos. Axions are created in the solar core via the Primakoff effect (Primakoff 1951), and this process also allows the axions to convert back into photons via coupling with an ambient magnetic field. In this interaction the resultant photon nearly preserves the incident momentum and energy of the axion. The solar axions mostly result from thermal photons in the core (X-rays) interacting with a nuclear field as a virtual photon, the escaping axion spectrum resembles the core blackbody distribution.

Many searches have been carried out for the solar axions, which are attractive observationally because the source is relatively nearby and the fluxes are (hypothetically) large. These searches individually cover different regions of the parameter space (the unknown axion mass, and its coupling constant $g_{a\gamma}$). These searches include ground-based "helioscopes" or "axion telescopes", of which the largest and most sensitive has been the *CERN Axion Solar Telescope* (CAST; Andriamonje et al. 2007). The ground-based searches rely upon powerful magnets to convert the axions; the CERN magnet has a field of about 9 T over a 10-m length.

In this paper we follow up on a pioneering search by Carlson & Li-Sheng (1996, see also Zioutas et al. 2009) for solar axions via solar X-ray observations. This search was carried out with the *Yohkoh* Soft X-ray Telescope (SXT; Tsuneta et al. 1991). Such a search makes use of the natural magnetism of the solar atmosphere as a converter. We extend this search with *Yohkoh* and describe also searches with RHESSI (Hannah et al. 2007b, 2010) and with *Hinode/XRT* (Section 4). In such searches one is at the mercy of the vagaries of the solar magnetic field for the conversion. The X-rays can propagate to near-Earth space where a solar X-ray telescope can detect them, provided that the conversion occurs high enough in the solar atmosphere for the photons to escape without being first absorbed. As described in Section 3, the search is sensitive to an axion mass range that depends upon density distribution in the atmosphere. The run density and field in the quiet solar atmosphere are not understood very precisely at present, and this is even truer of different solar features such as faculae that may have much stronger magnetic fields. We discuss the issues involved in this knowledge in Section 2. A successful detection of an unambiguous axion signal would be possible even knowing these properties, since the axion X-ray signatures are so specific, but it would not be very precise. Indeed solar physicists would immediately want to make use of this signature to study the solar magnetic field itself.

2. Solar Magnetism

The solar magnetic field is extremely complicated (e.g., Harvey 1993). Near the photosphere it is neither a simple dipole, as eclipse pictures during solar minimum suggest, nor is it random. We observe the solar magnetic field mainly via use of the Zeeman effect in photospheric spectral lines. It appears to consist of two independent components: the quiet Sun, in which the field is highly correlated with the visible convective motions in the photosphere, and the active regions. Sunspots come and go with the Hale cycle of alternating polarities, and the magnetic flux that first appears in the active regions as spots appears to diffuse away across the disk, ultimately concentrating in the polar regions on the solar-cycle time scale. This component of the field thus has large-scale ordering both in space and time. The active-region fields may be orders of magnitude greater than those of the quiet Sun. The density structure of the solar atmosphere depends on the magnetic field in a dynamic manner, and there is a high degree of variability on small scales. From this it is clear that to predict the axion conversion rate in detail is impossible, and we can only hope to estimate it statistically. Indeed, for the quiet Sun, it may be that MHD simulations (e.g., Abbett 2007) may provide the simplest approach to this problem.

In the meanwhile there are several possible approaches. Carlson & Li-Sheng (1996) simply assumed a dipole field consistent with the then-current understanding of the quiet-Sun field structure. The situation has changed dramatically in recent years, with the discovery of strong horizontal fields in the lower solar atmosphere (Hannah et al. 2007b; Lites et al. 2008). These fields have horizontal intensities of order 50 G, rather than the vertical intensities an order of magnitude weaker that were commonly assumed a decade ago (e.g., Cox 2000). Indeed, the small-scale field may be more intense still (Trujillo Bueno et al. 2004). This makes a drastic difference for the expected quiet-Sun flux owing to the B^2 conversion efficiency. Unfortunately, we have little understanding of the vertical structure of the small-scale fields.

In active regions the photospheric fields are easier to measure, and much stronger, but again the extension of their structure is not well understood. The active-region corona has a low plasma beta (below 10^{-3} for typical parameters), with relatively weak currents appearing to thread it, and so a potential-field approximation makes a plausible beginning (see Schrijver et al. 2008, for further discussion). But the distribution of matter within this field is complicated and there is no compelling theory that describes, for example, the coronal pressure as a function of position in an active region.

3. Axion Conversion

The X-ray opacity of the solar atmosphere at relevant energies largely results from the photoeffect, as shown in Fig. 1 (right), and $\tau = 1$ occurs low in the atmosphere. This corresponds to a relatively high density, depending upon the particular solar feature and its dynamics. The traditional approach to estimating this and other parameters is through standard "semi-empirical" modeling, which aims to reproduce the emergent spectrum with non-LTE radiative transfer but otherwise limited physics; such models are 1D and time-stationary. From Equation 6 of Zioutas et al. (2009) we derive

$$\mathrm{d}P(\varepsilon, h) = g_{\mathrm{a}\gamma}^2 \frac{B_\perp(h)^2}{q(h, m_\mathrm{a}, \varepsilon)^2 + \kappa(\varepsilon)^2/4}\, q(h, m_\mathrm{a}, \varepsilon) e^{-\tau(\varepsilon)}\, \mathrm{d}l \tag{1}$$

for the source function of the emergent X-ray photons, where $\kappa(\varepsilon)$ is the mass absorption coefficient. Here $q(h) = (m_\mathrm{a}^2 - m_\gamma^2)/2E_\mathrm{a}$, with m_γ the effective mass of the photon in natural units (Fig. 1, left), and $\tau(\varepsilon) = \int_h^\infty \kappa\, \mathrm{d}h$. Zioutas et al. also quote an approximate axion flux of

$$J_\mathrm{a} = \mathrm{d}\Phi_\mathrm{a}/\mathrm{d}E_\mathrm{a} = g_{10}^2\, 3.821 \times 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{keV}^{-1} (E_\mathrm{a}/\mathrm{keV})^3/(e^{E_\mathrm{a}/1.103\,\mathrm{keV}} - 1),$$

where $g_{10} = g_{\mathrm{a}\gamma}/10^{10}$ GeV. The observable X-ray flux $J_\varepsilon = \int_0^\infty J_\mathrm{a} \mathrm{d}P(\varepsilon, h) \mathrm{d}h \propto g_{10}^4$ because of the two conversions needed.

Axion conversion in the natural magnetic field of the Sun differs from that in controlled laboratory conditions. The values of $B_\perp$ and density, and hence m_γ, vary in an ill-known manner through the solar atmosphere. For the purposes of this paper we have approximated the magnetic field above the photosphere as a simple exponential with photospheric magnitudes of [100, 1500, 3000] G and scale heights of [1, 2, 10] Mm for three Fontenla (2009) semi-empirical models describing quiet Sun, facula, and sunspot

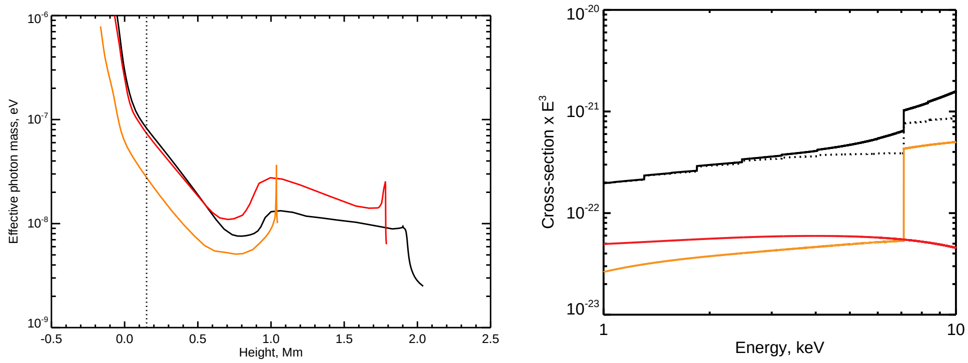

Figure 1. Parameters of the solar atmosphere. *Left:* effective photon mass in three standard solar model atmospheres from Fontenla et al. (2009)—in order of increasing transition-region height—sunspot umbra, facular region, and the quiet Sun. The dotted line shows the $\tau = 1$ height for 4.2 keV. *Right:* the absorption cross-section for X-rays in the quiet-Sun model. The photoeffect dominates in the 1-10 keV region; solid line shows the total and the lower lines He and Fe (with its K-edge); the dotted line shows the Thomson-scattering contributions. These cross-sections use Asplund et al. (2009) abundances in the quiet-Sun model and have been multiplied by E^3 for clarity.

umbra respectively. Figure 2 (left) shows contribution functions calculated for these models and for a range of assumed densities via Equation 1, and Fig. 2 (right) shows the three models considered. Both panels assume an axion mass of 1 μeV, and the variation with density mainly reflects the photoelectric absorption of the X-rays produced deep in the atmosphere.

4. The Searches

The solar axion source, modulo the complexities discussed in Sect. 2, should be an easy matter for X-ray astronomers. The source has well-defined signatures in space, energy, and time. Unfortunately the telescopes that we have for solar X-ray observation are not as sensitive as those used for non-solar X-ray astronomy, and there is competing emission from ordinary solar magnetic activity. Because of the latter problem, the most sensitive searches (those described below) are from sunspot minimum periods. In addition to the competition from solar activity (flares, microflares, X-ray bright points, and hot active regions), there is also a slowly-varying corona. In the absence of activity this background solar X-ray emission is so low that it cannot easily be measured (Peterson et al. 1966; Hannah et al. 2007b, 2010), and we do not know how bright the Sun is at the peak energy of the axion component, 4.2 keV (see Churazov et al. 2008, for a discussion of low-level solar emission).

The three solar X-ray telescopes used in the axion searches each have different properties, as described in the following sections. Generally the sensitivity of a given observation scales as the figure of merit (Peterson 1975) given by

$$\mathrm{FOM} = \sqrt{A \Delta t \varepsilon \Delta E / B}, \quad (2)$$

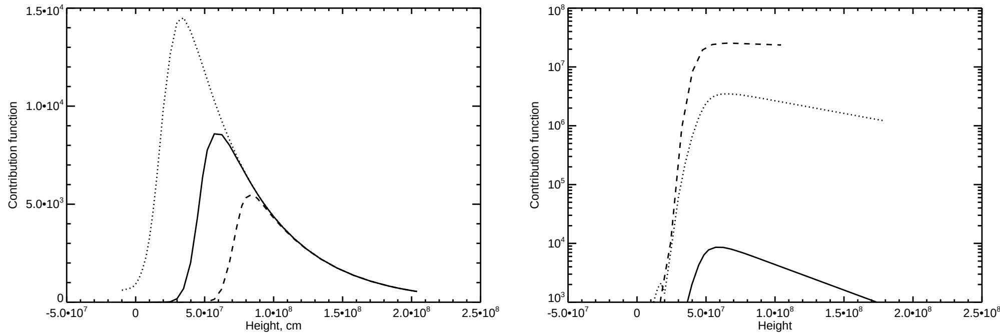

Figure 2. *Left:* the contribution function in the quiet-Sun model (solid), illustrating *ad hoc* 10× variations upward (dashed) and downward (dotted) in density relative to the quiet-Sun model. *Right:* contribution functions from the three models (dashed, umbra; dotted, facula; solid, quiet Sun).

Table 1. Properties of solar axion searches

Search	$\bar{E}$ (keV)	Area (cm^2)	Δt (s)	ΔE (keV)	Target
Yohkoh	2.1	0.78	2×10^5	1.0	Quiet Sun
RHESSI offpoint	4.5	1.1	1.03×10^6	3.0	Quiet Sun
RHESSI direct	4.5	30	—	3.0	Spots
GOES sunspots	4.2	2.3	—	3.5	Spots
Hinode/energy	1.53	2		0.7	Quiet Sun
Hinode/histogram	1.53	2		0.7	Quiet Sun

where A is the collecting area (cm^2), Δt the integration time (s), ε the detection efficiency, ΔE the spectral band (keV), and B the background counting rate in counts cm^{-2} s^{-1} keV^{-1}. We do not estimate the detection efficiency parameter ε, which refers to the quantum efficiency as well as other factors, such as the convolution of the telescope spectral response with the known spectral distribution of the axion source or the duty cycle of the observations. Table 1 summarizes some of the parameters for the search efforts discussed below. Note that the information in this table is inadequate, owing to limited space, for accurately estimating the figure of merit via Equation 2.

4.1. Simple Photometric Searches (the "Sunspot Flash")

Sunspot fields may attain many thousands of Gauss and have scales of tens of Mm, and so active regions are a good place to search for axionic X-rays (Carlson & Li-Sheng 1996). In principle as a sunspot group crosses disk center, it will become anomalously bright if axions are converting because of the B^2 dependence; the competition from ordinary forms of solar activity will also be intense but generally concentrated in lower photon energies. A search for a "sunspot flash" near disk center would preferably be done in hard X-rays and for an older sunspot region with relatively weak magnetic activity. We note that the umbral field tends to be vertical, which does not favor conversion, but that the field rapidly diverges and so large volumes of large $B_\perp$ will be available at times during the disk-center passage.

The standard GOES photometry, routinely available for decades, is biased towards short wavelengths in its 0.5–4 Å band (e.g., White et al. 2005). Thus it (as well as RHESSI) has a favorable spectral response. The spectrum of axion X-rays, integrated over the two GOES spectral bands, yields a hardness ratio of about 2; by contrast the usual optically-thin thermal spectra due to solar plasma activity have hardness ratios of order 0.001–0.01, depending upon the plasma temperature. As a zeroth-order check for axion presence, we have examined the two-channel GOES spectral ratio (nominally 0.5–4 Å and 1–8 Å) for several strong active regions and not seen any evidence of an axion-related flash at disk center. Such a search could also readily be carried out with RHESSI or SphinX (Sylwester et al. 2008) data and illustrates the use of the *spectral* and *temporal* signatures; the imaging instruments described below also employ the *spatial* signature to discriminate between axion-conversion and ordinary solar X-rays.

4.2. The *Yohkoh* Search

The *Yohkoh* SXT operated with a two-reflection mirror system at grazing incidence, and accumulated image charge on a 1024 × 1024-pixel CCD via shuttered exposures through metallic analysis filters to isolate given spectral ranges. In terms of the factors in Equation 2, the effective area of this instrument was about 0.78 cm^2 over a spectral bandwidth, depending on the filter chosen, of about 1 keV, effectively at a peak energy in the 1–2 keV range. Figure 3 shows the morphology of summed SXT soft X-ray images (Zioutas et al. 2009). The image on the left sums quiet periods from 1996, and the image on the right shows more active times. This view of the data is rather qualitative, but shows no evidence for excess emission due to axions.

The quantitative analysis of the image data is relatively simple. We take the most appropriate exposures, sum them up, and set limits on a source with the expected angular scale at disk center by differencing against the image external to this region; the time-series fluctuations in the pixel sums lead to an uncertainty and an estimate of the upper limit. We have obtained roughly 2 ksec of exposures in the AlMg filter (Tsuneta et al. 1991) during the quietest times in 1996, and from these images obtain an upper limit on the flux of 0.2 ph $(cm^2\ s\ keV)^{-1}$ at a mean energy 2.1 keV weighted against the photon spectrum of the axion source.

4.3. The RHESSI Search

The RHESSI instrument differs conceptually from a traditional soft X-ray telescope in that it employs modulation optics. Hannah et al. (2007a) describes the methods used for RHESSI quiet-Sun observations. This kind of optics permits observations to high energies, including γ rays, but has a high background rate because there is no focusing. Furthermore in the standard observing mode the net AΩ product for the extended axion source is reduced by the modulations necessary for image formation. The special observations devised for quiet-Sun viewing (Hannah et al. 2007a) require pointing RHESSI about 1° away from Sun center. Hannah et al. (2007b, 2010) have published the completed analysis for RHESSI observations taken in this mode in the recent solar minimum (2005–2009).

RHESSI searches for axion X-rays could also be made via its direct modulation in data from its low-resolution subcollimators. This would have the advantage of much longer integration times, since it would make use of essentially all of the data; in addition the data could be used to detect the "sunspot flashes" described in Section 4.1. Neither of these approaches has been followed yet.

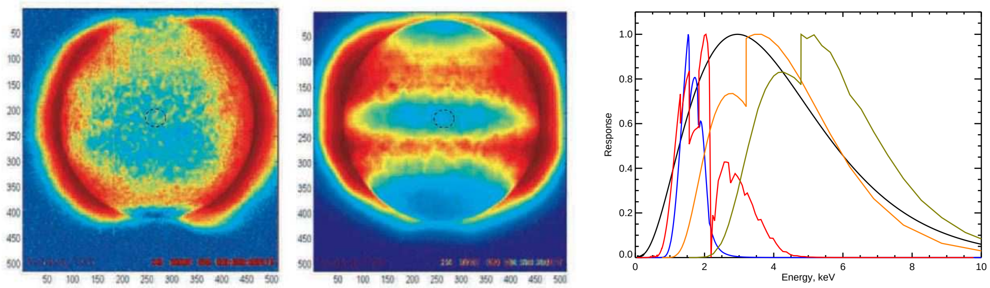

Figure 3. *Left:* quiet Sun, in a *Yohkoh*/SXT image search for axion-related soft X-rays. *Middle:* similar image sum for active times. The dotted circle at Sun center shows the location of the expected source (from Zioutas et al. 2009). *Right:* spectral passbands for the various searches—blue, the *Hinode*/XRT Be/Med filter; red, the *Yohkoh*/SXT AlMg filter; orange and olive, the GOES 1–8 Å and 0.4–4 Å passbands. All of these are normalized to their peak values and are weighted against the theoretical spectral distribution of the axions (black).

4.4. The *Hinode* Search

The *Hinode*/XRT instrument resembles SXT on *Yohkoh* in that it is a grazing-incidence soft X-ray telescope with CCD readout in energy mode. The lack of a mirror surface coating restricts XRT to a mean photon energy of about 1.53 keV, as weighted by the theoretical spectrum of the axions (Figure 3, right panel). During the recent solar minimum period XRT obtained almost 15 000 exposures in the "medium beryllium" filter, at 11.6 s exposure time in 8×8-pixel binning mode. These image parameters optimize transmission and suppression of readout noise in the camera. The net result is a total of more than 150 ksec exposure; this data set has the best sensitivity for solar axion detection by XRT.

The choice of filter and the low count rates allow us to attempt a novel spectral analysis of the data, namely the use of the pixel histograms to do pulse-height spectroscopy (e.g., Labonte & Reardon 2007) and thereby to decrease the background rate. This is possible even though XRT works in energy mode rather than as a photon counter. In this approach a sequence of images yields a signal histogram for each pixel. Read noise and dark noise populate the bottom range of the histogram, as do the $\sim$0.1–0.2 keV photons due to ordinary solar activity. The most common signal level, for these data, is determined by the read noise of the CCD. A single true photoelectron at the mean energy expected (determined by the convolution of the telescope efficiency vs. energy and the axionic X-ray spectrum) would have a larger signal; ideally this single-photoelectron response would produce an identifiable peak in the histogram. The $\sim$1.5 keV photons due to axion conversion would appear well above this noise level, and the observed rate of counts in these region of the histogram will have a background rate limited mainly by ordinary non-solar background sources such as Compton-scattered γ-rays, neutron-induced background, etc (see, e.g., Peterson 1975).

5. Discussion

The observations we have described have not yet positively identified any signature of solar axion emission, but considerable further work in refining these searches is

Table 2. Current X-ray limits (two sigma)

Search	$\bar{E}$ (keV)	Flux limit (ph cm^{-2} s^{-1} keV^{-1})	g_{10} limit (μeV)
GOES/long	3.6	—	—
GOES/short	4.8	—	—
Yohkoh/AlMg	2.04	1.2	0.4
RHESSI offpoint	5	340	1.8
RHESSI direct	5	—	—
Hinode/energy	1.53	0.1	0.3
Hinode/histogram	1.53	0.01	0.2

possible. Table 2 assembles representative values of the current upper limits derived from the various. The entries in the table are not definitive, except for the RHESSI "offpoint" entry, for which the observational work is essentially complete. As noted in Sect. 2, there are large unknowns in the physical parameters the conversion depends upon, specifically upon the structure of the solar magnetic field. To estimate the mass range we have taken the simplest case, the quiet Sun, and adopted reasonable guesses regarding the necessary physical parameters. These are that the horizontal field is 100 G at the photosphere and falls off exponentially with a scale height of 1 Mm, roughly the granulation scale. The assumed density structure for the quiet Sun follows Model 1001 of Fontenla et al. (2009).

Figure 4 shows the initial results from the three X-ray telescopes. The dotted line in the figure shows the limit that would be obtained for an axion signal equal to the estimated solar albedo due to cosmic X-rays (Churazov et al. 2008). This is a practical but not fundamental limit, since the spectral and spatial signatures of the axion signal would still be available for deeper explorations.

6. Conclusions

This paper is a progress report on deep searches for solar X-rays originating in axion emission from the core of the Sun, as converted in the magnetic field in the solar atmosphere by the Primakoff effect. None of the searches to date have revealed a definite signal, but the limits on the coupling constant for the Primakoff effect can rival those obtained with laboratory techniques for axion masses below about 10^{-4} μeV. The main emphasis here has been to describe the solar framework for these searches, rather than to give definitive upper limits. The limits, indeed, will be quite uncertain for some time given our lack of knowledge of the physical conditions in the solar atmosphere.

There are several lines of research that could improve on the present limits, notably the use of any of the three data sets available in searches for the sunspot flash signature (Carlson & Li-Sheng 1996, see Section 4.1). This kind of observation depends on the fortuitous occurrence of a large quiescent sunspot passing close to disk center, not a common occurrence because of the brevity (about one day) of the transit. Such searches could be carried out in many other databases of non-imaging solar X-ray data, preferably ones in which a useful spectral signature could be incorporated with the temporal signature due to the disk passage of sunspots. Here a temporal signature could also be applied to the search even below the (soft) limit imposed by the diffuse

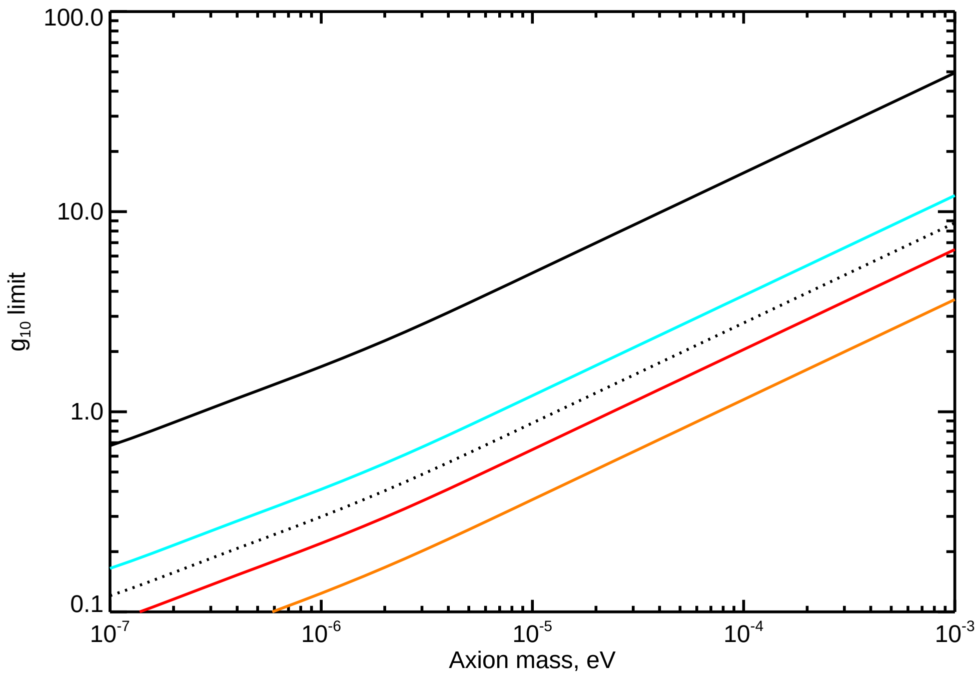

Figure 4. Comparison of limits on g_{10} from the three X-ray telescopes used for quiet-Sun integrations (RHESSI, black; SXT, blue; XRT, red and gold for direct and histogram methods). The dotted line shows the point of equality with the diffuse-component albedo as estimated by Churazov et al. (2008).

component. Another advantage of the sunspot fields is their extension into the corona, a volume not considered in the calculation of contribution functions given in this paper, and which will give correspondingly more sensitivity in the search.

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