QUIET-SUN X-RAYS AS SIGNATURE FOR NEW PARTICLES

K. Zioutas, K. Dennerl, L. DiLella, D. H. H. Hoffmann, J. Jacoby, and Th. Papaevangelou

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ABSTRACT

We have studied published data from the Yohkoh solar X-ray mission with the purpose of searching for signals from radiative decays of new, yet undiscovered massive neutral particles. This search is based on the prediction that solar axions of the Kaluza-Klein type should result in the emission of X-rays from the Sun direction beyond the limb with a characteristic radial distribution. These X-rays should be observed more easily during periods of quiet Sun. An additional signature is the observed emission of hard X-rays by the Solar Maximum Mission (SMM), the Near Earth Asteroid Rendezvous (NEAR), and RHESSI. The recent observation made by RHESSI of a continuous emission from the nonflaring Sun of X-rays in the 3 to ~15 keV range fits the generic axion scenario. This work also suggests new analyses of existing data in order to exclude instrumental effects; it provides the rationale for targeted observations with present and upcoming (solar) X-ray telescopes, which can provide the final answer to the nature of the signals considered here. Such measurements become more promising during the forthcoming solar cycle minimum with an increased number of quiet-Sun periods.

Subject headings: dark matter — elementary particles

On-line material: color figures

1. INTRODUCTION

In order to solve the strong charge parity (CP) problem (why the strong interaction contrary to weak interactions does not violate CP symmetry), a new neutral particle, the axion, with spin parity 0\textsuperscript{−} has been invented (for recent review articles, see, e.g., Raffelt 1999, 2000; Bradley et al. 2003). Axions, along with weakly interacting massive particles (WIMPs), are the two leading particle candidates for dark matter in the universe. If axions exist, they should be produced abundantly inside the solar core. An axion can be seen as a very light neutral pion ($\pi_0$), with rest mass $\sim 10^{-3}\pm 3$ eV c\textsuperscript{−2}. However, while the $\pi_0$ interacts strongly and decays to two photons with a mean lifetime of $\sim 10^{16}$ s, the axion interacts very feebly with matter and is expected to decay to two photons ($a \rightarrow 2\gamma$) with a lifetime much longer than the age of the universe. Therefore, detection techniques utilize the axion interaction with the electric field of atoms of underground detectors or strong magnetic fields in order to (coherently) convert them to real photons. In other words, electric or magnetic fields play the role of a catalyst, which can transform axions into detectable photons. If very light axions ($m \leq$ a few eV) are produced inside the Sun, their thermal energy peaks at $\sim 4.2$ keV and they are ultrarelativistic. They mostly stream out of the Sun and can only have an impact on the evolution of a star through the additional escaping energy (as happens with neutrinos).

However, in recent theories of extra dimensions, proposed as extensions of the standard model, the “conventional,” almost massless axions become as massive as the reaction energies involved. In the case of the solar axions, the expected mass spectrum of all the excited Kaluza-Klein (KK) states extends all the way to $\sim 10$ keV c\textsuperscript{−2} (Dienes, Dudas, & Gherghetta 2000; DiLella et al. 2000; DiLella & Zioutas 2003). These high KK masses imply a relatively shorter lifetime ($\tau \sim 10^{20}$ s) because of the $\tau \sim m^{-3}$ dependence. The underlying axion-photon-photon coupling constant, $g_{\alpha\gamma\gamma}$, which defines the interaction cross section with ordinary matter, is the same for the conventional, almost massless axion and for the massive KK axions. In this work, the KK axions are taken as a generic example of particles that can be created inside the hot solar core. A small fraction of them ($\sim 10^{-7}$, as estimated by DiLella & Zioutas (2003, hereafter DZ03), are extremely nonrelativistic, and they can be gravitationally trapped by the Sun itself in orbits where they accumulate over cosmic times. As shown in DZ03, their density increases enormously near the solar surface. The estimated mean distance of the KK axion population from the Sun surface is $\sim 6.2 R_\odot$.

If axions of the KK type are gravitationally trapped and decay to two photons,\textsuperscript{6} then the observed X-ray surface brightness from the solar disk and limb can be a signature of the solar axion scenario. In this work, we discuss the expected surface density profile of the derived axion halo around the Sun (DZ03), and we compare it with published data taken by the Yohkoh soft X-ray telescope from the diffuse emission of two quiet-Sun observations. In addition, the measured continuous emission of hard X-rays (below $\sim 15$ keV) from the nonflaring Sun during the past $\sim 25$ yr by different orbiting X-ray detectors is also considered.

2. THE SIGNATURES

2.1. Radial X-Ray Distribution

Assuming a spatial density distribution of radiatively decaying particles in the solar periphery, as described in DZ03, we calculate the surface X-ray flux expected from inside and

\textsuperscript{6} Following the decay mode $a \rightarrow \gamma\gamma$, the two photons have the same energy and are emitted back-to-back because of momentum conservation, since they are highly nonrelativistic.
outside the solar disk by integrating over the line of sight (see Fig. 1). In doing so, if the observed X-rays from the Sun direction are exclusively due to the radiative decay of massive nonrelativistic particles along the pointing direction, their density distribution can thus be derived. This is actually a standard procedure applied in astrophysics. The place around the solar limb, i.e., $R = 1 R_\odot$, provides a characteristic change in surface luminosity because of the rapid change of the integration path length of the strongly absorbed photons from axion decay.

Figure 2 shows the same axion simulation used in Figure 1, covering an elongation angle up to ~50° away from the Sun. The level of the cosmic X-ray background (XRB) relative to that expected to come from the Sun is also shown. The XRB, in fact, defines the size of the predicted solar X-ray halo within the axion model; for the hard and soft energy band, it extends to “only” ~3.5° and ~9°, respectively.

We therefore suggest that the detection of an extended X-ray halo around the Sun is a signature of KK axions produced in the core of the Sun, if the contributions from conventional solar dynamical effects, e.g., flares, can be excluded. The X-ray surface brightness resulting from the decay of trapped axions is expected to be continuous and stable with time and to decrease exponentially with increasing distance from the Sun (see Figs. 1 and 2). At first, this signature can be better studied during quiet-Sun conditions, because any contributions from the dynamic Sun can thus be minimized. These conditions correspond to the Yohkoh solar data that we have used in this work. However, beyond a certain distance from the solar limb where even the impact of the active Sun becomes negligible, one could continuously study the X-ray emission from the periphery of the Sun. The next solar cycle minimum with extended quiet-Sun periods can be utilized to perform such measurements. The field of view (FOV) of the X-ray telescope should cover the largest possible distances from the solar disk. The limited FOV of all imaging solar X-ray observatories (~1° at best) can be effectively widened by pointing away from the Sun center.

Figure 1 shows the spatial distribution of two observations made by the Yohkoh imaging detector in the soft X-ray band (0.25 ≤ $E_x$ ≤ 4 keV) (Sturrock, Wheatland, & Acton 1996, hereafter SWA96; Wheatland, Sturrock, & Acton 1997, hereafter WSA97). To the best of our knowledge, these are radially the most extended measurements of this kind from quiet-Sun regions published so far. These two regions were assigned as being “quiet” before this work; i.e., the selection was unbiased, and it appears that the approach of SWA96 and WSA97 was reasonable. However, it is crucial that possible contributions from active regions on the solar disk into the limb region due to scattering in the X-ray telescope be excluded because they give rise to a radial distribution similar to that expected from the decaying axions in the solar halo. The treatment of such far-scattering effects, based on a correction made by Hara et al. (1994) on the Yohkoh point-spread function (PSF), as it was determined by Martens, Acton, & Lemen (1995), reached the conclusion that bright nearby regions constitute a small but not insignificant fraction (WSA97).

The bulk of the published work from all solar instruments, operating for years in space, focuses on the flaring Sun, with the quiet Sun being almost overlooked. However, the soft X-ray energy band of the Yohkoh observatory overlaps with the lower energy range of the axion model, which gives a broad distribution peaking at ~5 keV (DZ03). Then these soft X-rays can be associated with particles of rest mass $2 \times E_x$ (a few keV); i.e., they may be used to test the axion scenario (DZ03), thus extending it to lower energies, even though we cannot argue quantitatively for this. From the solar axion Monte Carlo simulation, the radial distribution of the assumed KK axions is actually independent of the axion rest mass. Therefore, in this work we look first at the shape of the radial distribution of measured solar X-rays and compare it with the shape predicted by the axion model. Of course, once X-ray observations at higher energies become available, they will allow a more quantitative comparison between prediction and observation.

The region chosen during the 1992 May observation was cleaned from so-called X-ray brightenings, which were three small regions with enhanced X-ray intensity. Keeping in mind the off-limb scattering considerations given above, this cleaning might explain the surprisingly high degree of agreement of the shape of the radial distribution of the 1992 May run with that expected by the axion model, in comparison to the 1992 August observation (see Fig. 1). Therefore, the 1992 May...
measurement could be taken as the kind of evidence of the axion scenario we search for, if the flux diffusing out beyond the limb is really negligible. Therefore, the off-limb scattering issue must be looked at much more closely. In fact, Figure 2 of the work by Sturrock et al. (1996) also provides the estimated scattering component across the solar edge, which makes only a \(~25\%) change. The tail(s) of the PSF from one or more bright points on the solar disk could in principle cause the observed X-ray intensity off the limb. However, it actually seems difficult to reconcile this picture with the PSF tail(s) with the measured change in brightness by as much as by a factor of 4 across the solar disk. Therefore, compared to the 1992 August run, the evaluated data from 1992 May are distinguished for the purpose of this work. The measurement from 1992 August has the advantage of increasing the radial distance by a factor of 2, thus covering 1 solar radius beyond the limb. However, the agreement with the shape of the axion model is certainly not as good as is the case for the 1992 May run. This is not surprising, since such observations are affected by uncertainties such as the level of contamination by hidden active regions (see above) or contributions from bremsstrahlung and/or synchrotron radiation by the corona plasma, etc.

In addition, these observations were performed during a solar maximum, and the quiet Sun is not as quiet as during a solar minimum. Therefore, the observed degree of agreement between the two \textit{Yohkoh} observations and the axion model is even more surprising. To put it differently, let us assume that the variations between the two experimental curves in Figure 1 reflect the underlying fluctuations (whatever the reason) between two independent measurements. Although only these two measurements are available, it is not unreasonable to assume that the underlying distribution should be some curve between them. Then it would be more reasonable, because less biased, to compare our predictions with a curve obtained by the average of the two \textit{Yohkoh} observations. In fact, these two observations made \(~3.5\) months apart show fluctuations from the average of some \(\pm 30\%\), while the radial X-ray brightness changes by as much as a factor of \(~10\).

2.2. Quiet-Sun Hard X-Ray Emission

Interestingly, it has been recognized that the solar outer atmosphere is somehow continually and globally heated to MK temperatures; i.e., this heating is an ubiquitous quasi-steady-state activity (Moore et al. 1999). Here we discuss quiet-Sun X-ray observations with photon detectors in space. To find such data is not an easy task, since all relevant missions are primarily interested in solar flares. However, for this work such observations provide important information on the radial X-ray distribution.

The emission of X-rays above 3.5 keV from the nonflaring Sun was first observed in the 1980s by the hard X-ray imaging spectrometer (HXIS) on \textit{SMM} (Simnett 1998; G. M. Simnett 2003, private communication). Later (1996–2001), the \textit{Near Earth Asteroid Rendezvous} (\textit{NEAR}) spacecraft mission to the asteroid 433 Eros provided quiescent solar X-ray spectra: (1) directly with two solar monitors (Trombka et al. 1997; see Fig. 20); and (2) indirectly from the scattered solar X-rays by Eros (Trombka et al. 2000: see Fig. 2c; Starr et al. 2000: see Fig. 11). The analog X-ray spectra cover the \(~2\) to \(~10\) keV range.

The \textit{RHESSI} observatory (Hurford et al. 2002; Lin et al. 2002; see also Fig. 1 in Krucker et al. 2002) has confirmed these results: it has observed a \textit{continuous} X-ray emission, from 3 to \(~15\) keV, with frequent (every few minutes) microflaring (Lin et al. 2003), when there are no observable flares present (McTierman & Klimchuk 2003). This continuous emission of hard X-rays is consistent with the solar axion scenario behind this work. For example, Figure 3 gives the measured X-rays by the \textit{GOES} and \textit{RHESSI} missions in orbit; a jump in the low energy count rate between 3 and 12 keV when the \textit{RHESSI} day starts or ends, is clearly visible (Krucker et al. 2002). The \textit{GOES} X-ray satellite intensity above 3.1 keV is also at its lowest level (around 02:20, and there is no sign of a flaring Sun from either orbiting instrument. Since during this period the \textit{RHESSI} counting rate is clearly above the detector background level, this excess X-ray intensity comes from the nonflaring Sun.

Additional observations can be found in Lin (2003). Moreover, a statistical observation has been made with \(~1000\) such measurements (McTierman & Klimchuk 2003). The measuring time bin is 1 minute\(^{10}\) during detector daytime (with the Sun being in the \textit{RHESSI} FOV), and its low energy counting rate is taken at a minimum. In order to avoid microflares, a statistical flatness check was applied 1 minute before and after each interval. For the so-defined “quiet Sun,” a temperature distribution of \(~6–8\) MK is derived. Such

\begin{figure}
\centering
\includegraphics[width=0.8\textwidth]{fig3}
\caption{Top to Bottom: \textit{GOES} and \textit{RHESSI} X-ray observations during \(~1\) hr of low solar activity. The vertical lines define the spacecraft day. The \textit{RHESSI} detector background level is measured before and after the daylight part of the orbit (dashed line). The \textit{RHESSI} count spectrometer plot (bottom) is background-subtracted. This figure is taken from Krucker et al. (2002). [See the electronic edition of the Journal for a color version of this figure.]}\end{figure}
temperature values are well above the usually quoted quiet-Sun corona temperature of \( \sim 1 - 2 \) MK, and they may require careful interpretation.\(^{11}\)

2.3. Numerical Estimates

From Figure 3 one can perform an approximate intercalibration between RHESSI and GOES by using, for example, flare 2. The minimum rate above detector background around 02:15 is \( \sim 50 \) counts s\(^{-1}\), highly significant statistically. This corresponds to a brightness of \( \sim 2.6 \times 10^{-18} \) W m\(^{-2}\); i.e., the nonflaring solar X-ray luminosity in the range 3 - 12 keV is \( \sim 6 \times 10^{20} \) ergs s\(^{-1}\). One should note that the corresponding value used in the solar axion model was \( \sim 10^{23} \) ergs s\(^{-1}\) in the energy range 2 - 8 keV. Having in mind the relation\(^{12}\) between the X-ray luminosity and the axion-to-photon coupling constant \( L_X \sim (g_{\gamma\gamma})^4 \), the lower X-ray luminosity derived above implies a smaller coupling constant, \( g_{\gamma\gamma} \geq 2.5 \times 10^{-14} \) GeV\(^{-1}\). However, we made the assumption that flare 2 has the same X-ray energy spectrum as that from the nonflaring Sun. In fact, flares emit higher energy X-rays (as can be seen also in Fig. 3, bottom), while the RHESSI detection efficiency increases very rapidly with energy. This tends to underestimate the photon intensity for the nonflaring Sun, and therefore the above value for the coupling constant \( (g_{\gamma\gamma})^4 \) is a safe lower limit [a value of \( g_{\gamma\gamma} \sim (4 - 5) \times 10^{-14} \) GeV\(^{-1}\) might be reasonable].

Similarly, in order to derive a limit of the coupling constant \( g_{\gamma\gamma} \) from the Yohkoh observations, we assume that the axion model can be extended to the lower energy band of Yohkoh \( (E, \geq 0.5 \) keV\). The estimated quiet-Sun X-ray luminosity between \( \sim 0.5 \) and \( \sim 4 \) keV is\(^{13}\) \( L_X \approx 3.75 \times 10^{25} \) ergs s\(^{-1}\). This much higher solar soft X-ray brightness implies, again according to the \( L_X \sim (g_{\gamma\gamma})^4 \) relation, a larger coupling constant, i.e., \( g_{\gamma\gamma} \leq 40 \times 10^{-14} \) GeV\(^{-1}\), in order to achieve a normalization between the two Yohkoh observations and the axion model (DZ03) shown in Figure 1. The value of \( g_{\gamma\gamma} \) derived from the \( \sim 1 \) keV range is still \( \sim 500 \) times smaller than the best experimental limit obtained by the CERN Axion Solar Telescope (CAST) (Hoffmann 2003).\(^{14}\) For comparison, the corresponding value used in the solar axion model is \( g_{\gamma\gamma} = 9.2 \times 10^{-14} \) GeV\(^{-1}\). The implied simplifications of and/or assumptions with the RHESSI and Yohkoh results provide a wide range of allowed values for the coupling constant \( 2.5 \times 10^{-14} \) GeV\(^{-1} \leq g_{\gamma\gamma} \leq 40 \times 10^{-14} \) GeV\(^{-1}\), with the axion model value being within these loose bounds. Note that these are rough numerical estimates, and the solar axion model is a generic one.

3. DISCUSSION

The discovery by Grotrian (1939) that the solar corona is \( \sim 100 \) times hotter than the underlying photosphere has been a puzzle ever since. Remarkably, recent experimental work in this field arrives at the conclusion that the results have made the coronal heating process even more of a mystery (Antiochos et al. 2003). Various conventional approaches (see, e.g., Suzuki 2002) to understanding this strange finding have been suggested in order to explain the coronal heating. The physical origin of the coronal heating remains one of the most fundamental problems in stellar (and solar) astrophysics (Güdel et al. 2003).

The solar axion scenario provides a continuous and steady energy input into the solar atmosphere. However, depending on the local physical conditions, e.g., magnetic field strength, plasma density, etc., an additional axion-to-photon conversion mechanism may locally enhance this energy input. In addition, the derived density of the axion cloud is highest near the surface of the Sun. It is conceivable that with such a high density of boson states some additional as yet unforeseen effects might occur, which may be influenced by the physical environment. Then the phenomenology associated with more elaborated models might provide important feedback to the axion scenario. We mention, for example, models of small-scale reconnection processes (e.g., Sturrock 1999), which have seen much discussion in recent years (Suzuki 2002). These models might point to a specific local property of the solar atmosphere, which can have an impact on the ubiquitous trapped axions. Having in mind the solar neutrino problem, it might well be that the solar corona problem also points to a solution based on nonstandard (solar) physics. It is this approach that we follow in this work.

The radial distribution of the two independently measured Yohkoh images in soft X-rays and the axion model predictions (Fig. 1) appear quite similar, suggesting a possible correlation between them. Interestingly, the findings of the same two quiet-Sun investigations (SWA96; WSA97) also favor a mechanism that somehow deposits nonthermal energy as heat beyond the observed range of heights above the limb \( (R \geq 1.5 - 2 \) R\(_{\odot}\) in the quiet corona, consistent with an inward heat flux. Within the adopted model (SWA96; WSA97), there is no evidence for appreciable energy input over this radial range. However, an axion scenario, like the one used in this work, is consistent with these observations, including the continuous emission of hard X-rays from the quiet solar atmosphere. The observed X-rays below \( \sim 15 \) keV are much more energetic than the bulk of thermal photons from a \( \sim 2 \) MK solar corona plasma (e.g., \( E^{-1} \approx 3kT \approx 0.5 \) keV).

4. CONCLUSION

Our work suggests that the importance of quiet-Sun solar X-rays should not be overlooked. This paper should provide motivation for the solar X-ray community to experimentally follow the arguments presented here and to reduce the
The search for such a residual radiation from the solar disk direction might be the most sensitive approach, especially at photon energies above a few keV, where practically no emission is expected from the quiet Sun.

In summary, the radial distributions from the reconsidered two Yohkoh X-ray observations of the quiet Sun (including the derived inward heat flux in the solar atmosphere of some nonthermal energy deposition beyond ~1 solar radius from the Sun surface) can be reconciled with a halo of decaying massive particles near the solar surface. New analyses of existing data may definitely clarify that instrumental scattering effects from bright points on the solar disk are small. More extended radial X-ray distributions (preferentially during a solar cycle minimum) can provide important information for the quiet Sun. An additional and independent evidence in favor of the axion scenario is the observed continuous emission of X-rays from the nonflaring Sun in the 3 to ~15 keV range. All these observations, when considered together, might suggest an unconventional mechanism of the type assumed here. New X-ray measurements could clarify the nature of these relatively high energy effects around the Sun, for which an alternative conventional explanation is still missing.

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