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FIRST LIMITS ON THE 3–200 keV X-RAY SPECTRUM OF THE QUIET SUN USING *RHESSI*

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ABSTRACT

We present the first results using the *Reuven Ramaty High-Energy Solar Spectroscopic Imager* (*RHESSI*) to observe solar X-ray emission not associated with active regions, sunspots, or flares (the quiet Sun). Using a newly developed chopping technique (fan-beam modulation) during seven periods of offpointing between 2005 June and 2006 October, we obtained upper limits over 3–200 keV for the quietest times when the *GOES 12* 1–8 Å flux fell below 10^{-8} W m^{-2}. These values are smaller than previous limits in the 17–120 keV range and extend them to both lower and higher energies. The limit in 3–6 keV is consistent with a coronal temperature $\leq$6 MK. For quiet-Sun periods when the *GOES 12* 1–8 Å background flux was between 10^{-8} and 10^{-7} W m^{-2}, the *RHESSI* 3–6 keV flux correlates to this as a power law, with an index of 1.08 ± 0.13. The power-law correlation for microflares has a steeper index of 1.29 ± 0.06. We also discuss the possibility of observing quiet-Sun X-rays due to solar axions and use the *RHESSI* quiet-Sun limits to estimate the axion-to-photon coupling constant for two different axion emission scenarios.

Subject headings: elementary particles — Sun: activity — Sun: corona — Sun: X-rays, gamma rays

1. INTRODUCTION

The X-ray spectrum of the Sun free of sunspots, active regions, and flares (the quiet Sun) is an important yet elusive measurement, despite interest back to the earliest days of solar X-ray observations (e.g., Neupert 1969). Such an observation would provide insight into the nature of possible small-scale steady state energization processes in the solar corona. For *soft* X-rays (i.e., X-rays emitted by thermal sources as free-free, free-bound continua or lines), the solar corona is comparable to other stars (e.g., Pevtsov & Acton 2001). The stellar coronal emission consists of contributions from more than one physical component with an emission measure distributed over temperature. For *hard* X-rays (usually characterized by an arbitrary minimum photon energy instead of defined as nonthermal bremsstrahlung), there is only one reported observation, that of Peterson et al. (1966).

Observations of soft X-ray emission not associated with active regions, for instance, with the *Yohkoh* soft X-ray telescope (SXT), show X-ray bright points that are weak compared to active region emission (Strong et al. 1992). They are numerous, well dispersed across the solar disk, and associated with network boundaries. The presence of nonthermal electrons in these events has been inferred from radio observations (Krucker et al. 1997), but no hard X-ray emission was detected. This is because previous hard X-ray imaging observations (*Solar Maximum Mission* HXIS, *Hinotori*, and *Yohkoh* HXT) were optimized to study flares and were ill suited to observe weak sources distributed over large angular scales.

With small flares, i.e., microflares, the presence of nonthermal electrons has been confirmed by microwave (Gary et al. 1997) and *Reuven Ramaty High-Energy Solar Spectroscopic Imager* (*RHESSI*) hard X-ray observations (Krucker et al. 2002). Imaged *RHESSI* microflares are always associated with active regions (Hannah et al. 2006). Although we might expect hard X-ray emission from below the current limit of microflare observability, it is uncertain whether such a population would exist in the absence of active regions. It is speculated that still smaller nonthermal energy releases, such as "nanoflares" (Parker 1988), could produce globally distributed hard X-rays.

In addition to these processes, the interaction of cosmic rays in the solar atmosphere could also generate weak diffuse X-rays from the quiet Sun (Dolan & Fazio 1965; Seckel et al. 1991). Additional nuclear processes arising from such cosmic-ray interactions are likely to only produce minuscule X-ray emission; for instance, *inner bremsstrahlung* from β-decaying neutrons in the solar analog of the CRAND (Cosmic-Ray Albedo Neutron Decay) mechanism (MacKinnon 2007) is predicted to produce X-rays at a level far below that of the diffuse cosmic background, which is 10^{-4} to 10^{-8} photons s^{-1} cm^{-2} keV^{-1} from 3 to 100 keV over a solar disk area.

Axions (Weinberg 1978; Wilczek 1978) are hypothetical weakly interacting particles that could also produce an X-ray signature from the Sun (Sikivie 1983). Nuclear reactions in stellar cores should produce axions copiously; in the case of the Sun, the average energy of axions is 4.2 keV (van Bibber et al. 1989). These axions can convert directly to X-ray photons in a perpendicular magnetic field (Sikivie 1983), with the resulting photons having the same energy and momentum as the incident axion. Ground-based experiments using strong magnetic fields have tried to use this process to search for solar axions (Zioutas et al. 2005). The probability of this conversion is proportional to the square of the product of the axion-photon coupling, the distance traveled through a perpendicular magnetic field, and the strength of this field (Sikivie 1983). This raises the possibility of conversion in the corona (Carlson & Tseng 1996). Attempting to observe such a small flux would be difficult but would be more favorable during quiet-Sun periods when the conventional X-ray emission from the Sun is at a minimum.

RHESSI (Lin et al. 2002) has unprecedented sensitivity for

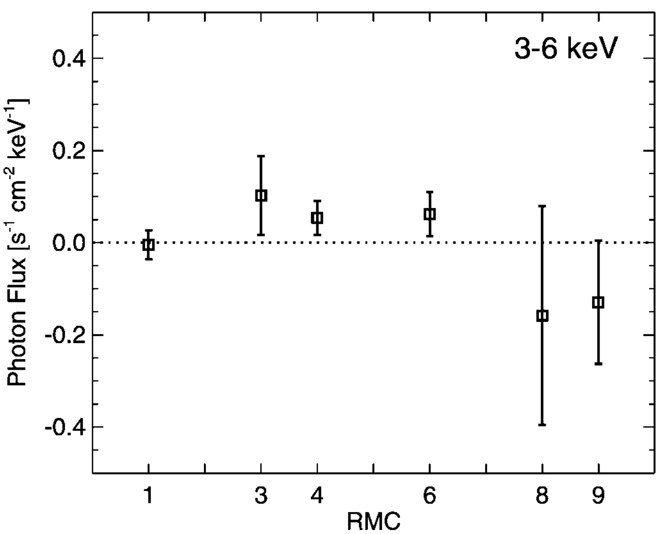

FIG. 1.—The 3–6 keV flux observed in each of *RHESSI*'s rotation modulation collimators (RMCs) averaged over the times when the *GOES 12* 1–8 Å flux was below the A1 class. The errors are larger with RMCs 8 and 9 since their field of view makes them less efficient for fan-beam modulation. The dotted line indicates the zero flux level, the case if there was no solar emission above the background.

3–25 keV X-rays because when its automated attenuators are "out" it can observe with the full area of its detectors. This was not possible for earlier instruments, which used fixed shielding to prevent excessive count rates from soft X-rays in flares. Normal *RHESSI* imaging is accomplished with a set of nine bigrid rotating modulation collimators (RMCs) with resolutions logarithmically spaced from 2.3″ to 183″. Each RMC time modulates sources whose size scale is smaller than their resolution. Thus, despite its sensitivity, *RHESSI* is not well suited to observe weak sources larger than ∼3′. Most potential mechanisms for quiet-Sun emission would be expected to be weak and well dispersed across the 32′ solar disk.

For weak sources, it is essential to distinguish counts due to solar photons from counts due to terrestrial, cosmic, or instrumental background. We adopt an offpointing technique called *fan-beam modulation* (Hannah et al. 2007), which provides a time-modulated, or "chopped," signal of the solar disk, allowing us to distinguish distributed solar emission from the background.

In this Letter, we detail the first analysis of periods of quiet Sun with *RHESSI* using the fan-beam modulation technique (§ 2). We present the first limits of the quiet-Sun X-ray spectrum and show how this correlates with the *GOES 12* 1–8 Å flux and *RHESSI* microflares in § 3. In § 4, we discuss the X-ray emission due to solar axions, and in § 5 we discuss the further work that can be achieved using fan-beam modulation during solar minimum conditions.

2. FAN-BEAM MODULATION TECHNIQUE

Instead of using the rapid time modulation associated with its RMCs, fan-beam modulation is based on a secondary modulation that results from the finite thickness of *RHESSI*'s collimator grids (Hurford et al. 2002). Fan-beam modulation depends on the offpointing angle, with a maximum effect when *RHESSI* is between 0.4° and 1° from offpointed Sun center (Hannah et al. 2007). This "envelope" modulation peaks twice every rotation when the slits of the grids are parallel to the line between the *RHESSI* pointing and source center, producing two transmission maxima per rotation. For a period of offpointing, we bin (or "stack") the data in a chosen energy range according to the roll angle of the spacecraft. These data are fitted with the expected modulation, and the resulting amplitude is corrected for the predicted grid transmission efficiency. This technique works best in *RHESSI*'s RMC with the narrowest field of view, RMCs 1–6. In addition, RMCs 2, 5, and 7 are not used in this analysis as they have the poorest energy response.

This type of observation has been done for a total of 45 days during seven periods (2005 July 19–26, 2005 October 18–28, 2006 January 12–17, 2006 February 1–7, 2006 August 3–8, 2006 September 26–29, and 2006 October 12–23), when the *GOES 12* 1–8 Å flux was around 10^{-8} W m^{-2} and no active regions or spots were on the disk. The Sun was very quiet during these periods with the microwave emission (F10.7 levels) in the range 70–78 solar flux units and the *GOES 12* 1–8 Å flux "flat-lining" below 10^{-8} W m^{-2}, the equivalent of an A1 class flare.

The data set was divided into 5 minute time intervals, which are short enough so that the radial offset, and hence grid transmission factor, changes little. For the quiet-Sun results presented in this Letter, we have removed intervals with sharp time-series features (such as flares or particle events). The analysis was further restricted to times when *RHESSI* is at the lowest latitudes in its orbit, to minimize the terrestrial background. From these four offpointing periods, we have a total of 1774 5 minute time intervals (over 147 hr of data), 1071 (or 89.25 hr) of which occurred while the *GOES 12* 1–8 Å flux was below the A1 class of 10^{-8} W m^{-2}. For each of these time intervals, and over chosen energy bands, we have an amplitude of the quiet-Sun count rate corrected for the transmission through *RHESSI*'s grids. The resulting fitted amplitudes are then combined from different time intervals to improve the signal-to-noise ratio before conversion to a final photon flux using the diagonal elements of the appropriate detector response matrix (Smith et al. 2002).

3. *RHESSI* QUIET-SUN SPECTRUM

Figure 1 shows the average 3–6 keV emission for six of *RHESSI*'s detectors. There is a small scatter between the detectors but consistent to within the errors. To calculate the average overall flux for each energy band, we use the weighted mean of the value found in RMCs 1, 3, 4, and 6 and give the error as the standard deviation in this weighted mean. Table 1 shows these values for energy bands between 3 and 200 keV during the quietest times.

None of the values given in Table 1 show a clear statistical significance. Therefore, we do not claim detection of a signal from the quiet Sun but rather give conservative 2 σ upper limits to the quiet-Sun emission using the errors given in Table 1, shown in Figure 2. The dotted histogram shows the data of Peterson et al. (1966), who made pioneering solar hard X-ray observations with balloon-borne scintillation counters, in the 17–120 keV range. Our hard X-ray upper limits improve on these results to about 75 keV and are consistent with them above this energy. Our results also extend the energy range into the previously unmeasured domains below 17 keV and above 120 keV.

Figure 2 also shows four CHIANTI thermal spectral models for coronal emission (Dere et al. 1997; Landi & Phillips 2006). For each assumed temperature, the emission measure is constrained by *Yohkoh* SXT observations, which was sensitive to

TABLE 1
THE WEIGHTED MEAN, AND ITS ASSOCIATED STANDARD DEVIATION, OF QUIET-SUN PHOTON FLUX

Energy (keV)	Weighted Mean (10^{-4} photons s^{-1} cm^{-2} keV^{-1})	σ (10^{-4} photons s^{-1} cm^{-2} keV^{-1})
3–6	330.99	±207.25
6–12	−5.24	±8.46
12–25	−0.73	±1.34
25–50	0.14	±0.63
50–100	0.74	±0.54
100–200	−0.79	±0.42

NOTE.—When the *GOES 12* 1–8 Å flux <10^{-8} W m^{-2}.

1–2 keV X-rays, during solar minimum (Pevtsov & Acton 2001). The *RHESSI* limit in 3–6 keV is consistent with a quiet coronal temperature ≤6 MK.

We can gain a better understanding of possible quiet-Sun X-ray emission by using all 1774 5 minute time intervals, not just the quietest periods. These quiet-Sun observations occurred over a range of *GOES 12* 1–8 Å background fluxes up to 10^{-7} W m^{-2} and still in the absence of active regions. By calculating the *RHESSI* flux in consecutive subsets of *GOES 12* background fluxes, we can plot the correlation of *RHESSI* quiet-Sun 3–6 keV flux to *GOES 12*, shown by the broad crosses in Figure 3. The errors shown here are the statistical ones found from the fit errors from each time interval combined in quadrature. There is a clear power-law correlation between the *GOES 12* and *RHESSI* data, with an index of $\gamma = 1.08 \pm 0.13$.

To put these observations in context, we have also shown, as the square data points in Figure 3, the fluxes for eight microflares that occurred during quiet-Sun offpointing. The times of these microflares were excluded from our quiet-Sun 5 minute time intervals, since they are a sign of activity. We used the fan-beam modulation technique for 16 s about the peak of these flares and plotted the flux against the corresponding background-subtracted *GOES 12* flux. The *RHESSI* flux from these microflares is around 2 orders of magnitude larger than the quiet-Sun values, and there is again a power-law correlation between *RHESSI* and *GOES 12*. The microflare power-law correlation with *GOES 12* is slightly steeper (1.29 ± 0.06) than that of the quiet Sun.

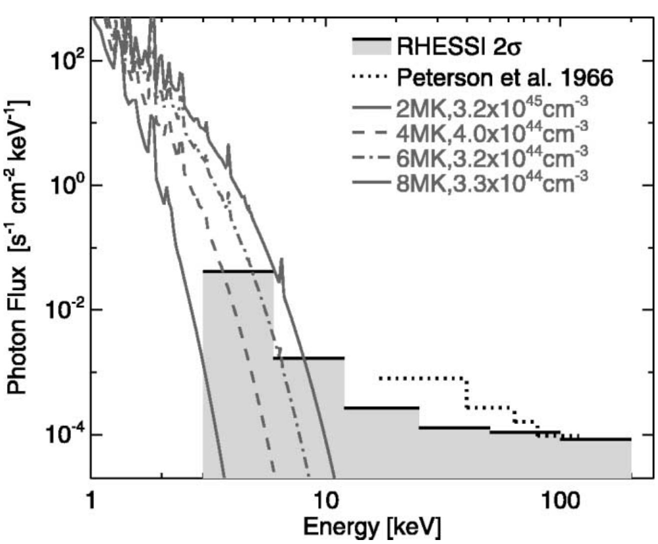

FIG. 2.—The 2 σ upper limits of the quiet-Sun photon flux spectrum, calculated using the *RHESSI* time intervals when the *GOES 12* flux in the 1–8 Å band fell below the A1 class, 10^{-8} W m^{-2}. The values shown are the 2 σ limits, from the standard deviation of the weighted mean of the four RMCs. The Peterson et al. (1966) limits are quoted as having a "95% confidence." The four thermal spectra are CHIANTI models using an observation of the quiet corona with *Yohkoh* SXT (Pevtsov & Acton 2001), to constrain the possible temperature and emission measures.

4. SOLAR AXIONS

Axions emitted from the burning core of the Sun may be converted to X-rays by its own coronal magnetic field (Carlson & Tseng 1996), thus providing a detectable signal during periods of solar quiescence. The Sun's general field is constant and well constrained during quiet periods, and so it should be possible to derive a robust limit on the axion-photon coupling $g_{a\gamma\gamma}$, provided that other conventional solar mechanisms can be convincingly excluded.

Carlson & Tseng (1996) calculated whether such X-ray emission was observable by assuming $g_{a\gamma\gamma} = 10^{-10}$ GeV^{-1} and a dipole field scaled from a 10^{-4} T polar field, predicting a flux of 4×10^{-2} photons s^{-1} cm^{-2} keV^{-1} over 3–6 keV. This is valid for the case of sufficiently light axions, i.e., $m_a < 1.8 \times 10^{-6}$ eV. This X-ray flux is comparable to the value given in Table 1. The $g_{a\gamma\gamma}$ used in this calculation is similar to those cited by Zioutas et al. (2005) in a direct search for solar axions and the best bounds from stellar evolution, i.e., those from

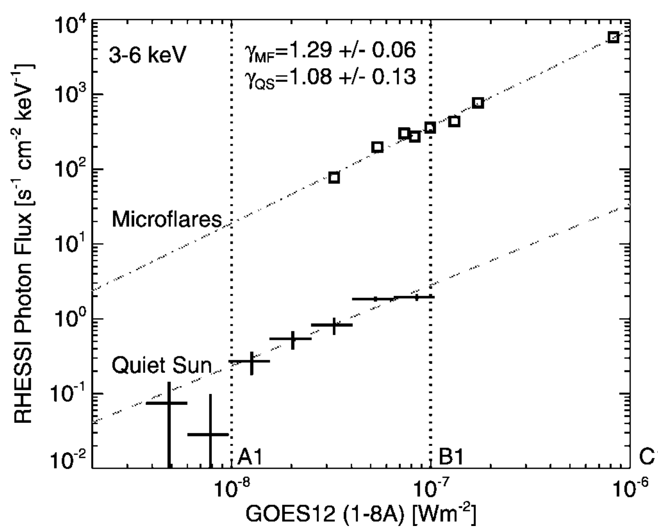

FIG. 3.—The 3–6 keV photon flux from the fan-beam modulation technique for the quiet Sun (*broad crosses*) and eight microflares during offpointing (*square data points*) as compared to the corresponding 1–8 Å *GOES 12* flux. The *GOES 12* flux for the microflares is background subtracted. The fitted line for the quiet-Sun points uses the five data points above the *GOES 12* A1 class: below this level, the *GOES 12* data digitizes as it reaches its sensitivity limit.

horizontal-branch stars (Raffelt 1996, 2006). This indicates that the *RHESSI* limit is consistent with other approaches, albeit for smaller axion masses.

Zioutas et al. (2004) published limits utilizing *RHESSI* data, constraining massive Kaluza-Klein (KK) axions, which arise in certain theories of large extra dimensions, in a scenario where KK axions are emitted from the Sun in gravitationally bound orbits, and subsequently undergo free-space decay $a \rightarrow \gamma\gamma$. Their value of $g_{a\gamma\gamma}$, however, was derived from *RHESSI* data taken during solar maximum and had not been corrected for instrumental response. Using the flux estimate in Table 1, we obtain an X-ray luminosity about 2 orders of magnitude smaller than the value cited by Zioutas et al. (2004); repeating their calculation, we find a somewhat smaller limit to the axion-photon coupling constant within this scenario of $g_{a\gamma\gamma} \ll 6 \times 10^{-15}$ GeV^{-1}.

5. DISCUSSION AND CONCLUSIONS

We have established new upper limits on quiet-Sun emission in hard X-rays when activity levels were below the *GOES 12* A1 class. The most natural explanation of such possible emission is that of unresolved microflares. Figure 3 however, indicates that such emission would require an ensemble of very small microflares, as the *RHESSI* flux for resolved microflares is over 2 orders larger than that of the quiet Sun. In this regime, the energy release maybe due to a mechanism physically different from (micro-)flares, such as the speculated nanoflares (Parker 1988). These quiet-Sun limits must be interpreted in terms of our knowledge of the distribution function of flare magnitudes, which follows a flat power law (Hudson 1991). The comparisons in Figure 3 would then yield a normalization of the distribution law (e.g., the constant multiplier in the power-law distribution). This will be calculated once the *RHESSI* microflare distribution is known—such a study is near completion (Hannah et al. 2006).

The work presented here represents the first use of the *fan-beam modulation technique* and shows that this method opens a new regime of observations for *RHESSI*, namely, weak sources larger than 3′ in size. Further use of this technique during the quieter times of solar minimum should help improve the limits presented here.

The detection of the component of the solar X-ray flux due to axions converting in the coronal magnetic field is especially challenging. Carlson & Tseng (1996) suggested that the stronger magnetic fields associated with sunspots should permit tighter limits and are valid up to higher values of the axion mass. However, such limits would be subject to greater uncertainties associated with the modeling of these magnetic fields. Using *RHESSI* to search for this emission due to axions may be more effective despite the large background from conventional emission since we know the characteristic spatial scale (i.e., core size) on which the emission is expected to occur (van Bibber et al. 1989) and it should vary in a distinctive manner as the sunspot moves across the solar disk. Given *RHESSI*'s low Earth orbit, it may be preferable to observe the X-rays produced through the conversion of axions in Earth's nightside magnetic field (Davoudiasl & Huber 2006). This method has the advantage that the Earth blocks the competing solar X-ray flux.

A detailed presentation of *RHESSI* limits on solar axions from both daytime and nighttime observations of the Sun will be the subject of a subsequent paper.

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