ABSTRACT

The axion is a promising dark matter candidate as well as a solution to the strong charge-parity (CP) problem in quantum chromodynamics (QCD). Therefore, discovery of axions will have far-reaching consequences in astrophysics, cosmology and particle physics. We describe a new concept for SmallSat Solar Axion X-ray Telescope (SSAXI) to search for solar axions or axion-like particles (ALPs). Axions or ALPs are expected to emerge abundantly from the core of stars like the Sun. SSAXI employs Miniature lightweight Wolter-I focusing X-ray optics (MiXO) and monolithic CMOS X-ray sensors to form a sensitive X-ray imaging spectrometer in a compact package (~10 x 10 x 60 cm). The wide energy range (~0.5 – 5 keV) of SSAXI is suitable for capturing the prime spectral feature of axion-converted X-rays (peaking at ~3 – 4 keV) from solar X-ray spectra. The high angular resolution (~30 arcsec) and large field of view (~40 arcmin) in SSAXI will easily resolve the enhanced X-ray flux over the 3 arcmin wide solar core while fully covering the X-ray activity over the entire solar disc.

INTRODUCTION

Modern cosmology firmly establishes that dark matter makes up 27% of the total energy budget or 85% of the total matter in the Universe. In spite of its abundance, the nature of dark matter remains one of the fundamental mysteries in astrophysics and cosmology and cannot be explained within the otherwise very successful Standard Model of particle physics. Currently the leading candidates for dark matter are Weakly Interacting Massive Particles (WIMPs), axions and sterile neutrinos.

Originally postulated by Peccei and Quinn, the axion is a hypothetical elementary particle arising from the most viable solution for the strong charge-parity (CP) problem in quantum chromodynamics (QCD). Since standard axions of a symmetry-breaking scale (of the
order of the electroweak interaction) were ruled out\textsuperscript{3,4}, newer models of arbitrary scales were developed by Kim-Shifman-Vainshtein-Zakharov (KSVZ)\textsuperscript{5,6} and Dine-Fischler-Srednicki-Zhitnitskii (DFSZ).\textsuperscript{7,8} These lighter axions, and the more general ALPs, which are well motivated by string theory, are postulated to interact so weakly that they are called “invisible”. Nevertheless, these theoretically inspired axions or ALPs would have far-reaching consequences in astrophysics and cosmology. For instance, ALPs, which are expected to be generated in the hot thermal plasma of stellar cores, provide a new process of energy loss in stellar evolution.\textsuperscript{9} ALPs are also proposed as a solution to the apparent transparency of the Universe to very high energy TeV gamma-rays.\textsuperscript{10} It has been suggested that efficient conversion of photons to ALPs expected in the high magnetic field of atmospheres of compact objects such as magnetars can lead to distinct spectral absorption signatures.\textsuperscript{11} Alternatively, axions could be generated within neutron stars by nucleon-nucleon bremsstrahlung, and spectral signatures from their decay into gamma-rays can be used to constrain the axion mass.\textsuperscript{12}

According to inflation theory, primordial axions of low kinetic energy should have been created abundantly.\textsuperscript{13} These primordial axions of low mass (< ~1 meV) are a particularly attractive candidate for dark matter because many would have survived and filled the universe because of their lack of a decay process into lighter particles.\textsuperscript{14}

Given the fact that the axion is a promising candidate for dark matter and a solution for the strong CP problem in QCD along with its numerous implications in astrophysics, many experimental techniques have been developed over the years for the search for axions or ALPs. These techniques include solar axion searches using ‘helioscopes’ (e.g., \textit{CAST}, \textit{IAXO}), polarization changes of light propagation in the magnetic field (e.g., \textit{PVLAS}), light shining through barriers (e.g., \textit{ALPS-I, II}), resonance effects in Josephson junctions (e.g., \textit{ORGAN}), electron recoils in cryogenic detectors (e.g., \textit{CDMS}).

We introduce a new mission concept, SmallSat Solar Axion X-ray Imager (\textit{SSAXI}) that is designed to search for axions or ALPs emerging from the solar core by capturing axion or ALP-converted X-rays in the solar magnetic field and thus effectively imaging the solar core.

**MOTIVATION AND OBJECTIVES**

**Axion emerging from the Solar Core**

Among many experimental techniques that have been developed over the years for the search of axions, solar axions are a primary target for many axion hunters. ALPs are expected to emerge abundantly from the hot plasma in the stellar core through the incoherent Primakoff effect, where a photon converts into an axion in the electric field of a charged particle. The emerging axions have a blackbody distribution of the thermal conditions in the solar interior with the peak and mean energies of roughly 3 and 4 keV, respectively. Almost all of axion search methods rely on the inverse coherent Primakoff effect, where an ALP, otherwise invisible, is re-converted to an X-ray photon by transverse magnetic fields. In the case of solar axions, this conversion can occur in the magnetic fields in the solar atmosphere, or laboratory magnetic fields.

**Fig. 1A** compares the solar X-ray spectra during a quiet sun state (A4: \(~4 \times 10^{-8} \text{ W m}^{-2}\)) and a “deep solar minimum” state (\(<\text{A1: ~7}\times 10^{-10} \text{ W m}^{-2}\)) with the
expected axion-converted X-ray fluxes from the central 0.1 $R_\odot$ disc (~50% of the total). The latter is proportional to $g^4 (B L)^2$ where $g$, $B$ and $L$ is the axion-photon coupling constant, the magnetic field strength and conversion length, respectively. Given the size of the solar core and the expected axion-converted X-ray spectra, the axion or ALP-induced X-ray signature can be determined decisively when it is simultaneously spatially resolved and spectrally detected with a sensitive soft X-ray imaging spectrometer (Fig. 1B), whereas the imaging or spectral signature alone is difficult to detect or allow other interpretations.

**Fig. 2** shows the combined solar images in a soft X-ray band during the solar minimum in 1996 and the solar maximum in 2001 taken with Yohkoh. The black circles at the center are the region of the expected enhancement in the X-ray flux from axion or ALP conversion.9 Both images show no enhancement at the center, and instead exhibit strong brightening at the rim of the solar disc while high X-ray activities are observed over a wide band near $\pm 35^\circ$ in latitude during the solar maximum.

**Fig. 3** compares the exclusion region in the coupling ($g$) versus axion mass space set by various experiments overlaid with the expected performance (preliminary) of a 100 ks NuSTAR observation (cyan; 75% dead time) and a 1 yr SSAXI observation (12U CubeSat version) near a solar minimum (red; 70% duty cycle).

**Sterile Neutrino**

The design of the SSAXI concept can be also optimized for search of the keV-scale sterile neutrino, another promising candidate for dark matter. Motivated by neutrino mass and oscillation measurements, sterile neutrino dark matter would decay via neutrino mixing into a photon and an active neutrino, producing a mono-energetic photon signature at $E = m_\nu/2$. Astrophysical X-ray observations have produced the most stringent constraints on sterile neutrino decay across a wide mass range,17 with other significant constraints from structure formation.18 In recent years, an exciting, but controversial, signal of sterile neutrino decay has been reported at $E \sim 3.5$ keV. This signal has been independently observed in stacked X-ray clusters, the Perseus Cluster, Andromeda, the Galactic Center, and the Galactic halo.19,20 If confirmed, such a discovery would be revolutionary for the fields of particle physics, astrophysics, and cosmology. However, initial analysis with the brief Hitomi dataset disputes this...
claim. The recent constraints on sterile neutrino decay set by the NuSTAR observations of the Galactic center were utilizing only zero-bounce photons, collected by ~ 5 – 10 cm² effective area. This shows that a dedicated continuous observation with a compact telescope of a moderate effective area would make significant improvement; the X-ray energy resolution (<~150 eV) in the range 3 – 4 keV, which the SSAXI concept would provide, is sufficient to resolve this controversy.

INSTRUMENT DESIGN

Fig. 4 illustrates a 12U CubeSat version of the SSAXI spacecraft (S/C) with the main instrument, an X-ray Imaging Spectrometer (XIS). The XIS is a compact focusing X-ray telescope in a small form factor (~10 × 10 × 60 cm, ~6U), weighing about 5 kg. It consists of Miniature Wolter-I X-ray Optics (MiXO) and a CMOS X-ray Active Pixel Sensor (APS). MiXO, configured for a focal length of 50 cm, provides a wide field of view (~40 arcmin dia.) with a high angular resolution (~30 – 60 arcsec) over the 0.5 – 5 keV band. The CMOS X-ray sensor covers the same band with a good energy resolution (<150 eV at 2 keV). A thick optical blocking filter attenuates high solar soft X-ray flux (<1.5 keV) while allowing >~50% of hard X-ray flux (>~3 keV) for efficient detection of axion-converted hard X-rays.

Table 1 summarizes key parameters of the SSAXI XIS for two possible configurations. A SmallSat S/C with a larger payload capability can accommodate multiple units of the XIS with a longer focal length. For instance, the MicroSat S/C developed by Blue Canyon Technologies (BCT) allows a payload volume and mass of ~45 × 45 × 80 cm and ~50 kg, respectively, and it can easily carry 3 XIS of 70 cm focal length. The 3 XIS can have different X-ray filters to optimize their sensitivity to different solar flare states and the energy band pass to cover a wide range of solar states.

Miniature X-ray Optics

Modern X-ray astronomy missions utilize grazing-incidence optics with Wolter-I geometries, which combines reflections from a parabolic and a hyperbolic surface of a barrel shaped mirror to reduce off-axis aberrations (over a single bounce system) for imaging. To increase the collecting area of these telescopes, several barrel shaped mirrors of varying diameter can be nested one inside the other along the same optical axis. While the conventional X-ray telescopes such as Chandra X-ray Observatory and XMM-Newton consists of very large X-ray optics with 7 – 10 m focal length, the advances in the X-ray optics technology over the years now enables a compact, yet powerful X-ray optic. SSAXI employs Miniature X-ray Optics (MiXO), compact lightweight Wolter-I X-ray optics for CubeSat/SmallSat missions. MiXO leverages the recent and on-going development to build lightweight Wolter-I X-ray optics based on the electroformed Ni-alloy replication (ENR) technique. In ENR, NiCo shells are electroformed from a precision machined mandrel.

![Fig. 4](left) SmallSat Solar Axion X-ray Imager (SSAXI) spacecraft with an X-ray Imaging Spectrometer (XIS), weighing 11 kg in a 20 x 10 x 60 cm form factor (~12U). (right) Main subsystems of the XIS.
and released through a thermal cycle (chilled water). The surface quality of the shells is determined by the mandrel surface and the figure of the shells is determined by the mandrel figure coupled with the stress during the release process.

**Fig. 5** illustrates the design concept for MiXO on SSAXI, where the optics consist of ten 250 µm thick NiCo shells in an optics housing and “spider” support structure. The overall structure including the housing fits inside of a 1U volume with ~10 cm dia. × 9 cm length (Fig. 5A). Each shell has slightly different length depending on the shell radius, a.k.a. a butterfly design, to allow a wide field of view (FoV~40 arcmin dia.) with high angular resolution (Fig. 5B).

The configuration should enable ~2 cm² on-axis effective area in the 3 – 4 keV band within 30 – 40 arcsec HPD after a thick optical blocking filter (roughly equivalent to a ~250 µm thick Be window). The thick filter is required to suppress soft X-rays below 1 – 1.5 keV, which otherwise dominate the X-ray flux and cause pile-ups on the CMOS X-ray sensors.

**CMOS X-ray Sensors**

**Fig. 6** shows the focal plane design of the SSAXI XIS, which consists of the frontend and backend electronics boxes. The SSAXI XIS focal plane is based on a monolithic CMOS X-ray APS, which is known as “Big Minimal III” (BM-III). CMOS X-ray sensors are becoming the next state-of-art detectors for X-ray telescopes, just as CMOS optical sensors like devices in SoloHi and WISPR are replacing CCD imagers. The BM-III devices were designed by SRI/Sarnoff and share a common heritage with the flight CMOS imagers provided by SRI for other programs.

The back-illuminated BM III devices with 10 – 20 µm thick Si absorber have sufficient QE over the 0.5 – 7 keV band that can separate the axion or ALP-converted X-rays peaking at 3 – 4 keV from the soft solar X-ray spectra. The fast readout in the BM-III devices enables high spectral resolution at high temperature. Forgiving thermal requirements are suitable for resource-limited SmallSats. It also enables a wide dynamic range without pile-ups, which is essential for observing highly variable solar X-ray activities. Small pixel size (~6 arcsec per pixel for a focal length of 50 cm) is sufficient to oversample the MiXO point spread function (PSF ~30 arcsec HPD at on-axis). Each pixel has its own electronics channel (i.e., Active Pixel Sensor), eliminating the need for long charge transfers, and making the device inherently radiation tolerant (>100 krads), which is ideal for space applications.

Each BM-III device has a 1k × 1k array of 16 µm 6-Transistor Pinned Photo Diode (6T PPD) pixels. The BM-III 1k × 1k array consists of two 512 columns × 1k row halves. Each half has its own 512 column-at-a-time, clamp-and-sample analog Correlated Double Sampling (CDS) processor. Each 512-column processor then reduces to a single buffered output via a 512:1 multiplexer. The maximum possible rate from each output is ~20 MHz (per pixel). The maximum possible read rate of a full frame, with two output channels operating, is therefore 40 Hz (per frame). For the SSAXI focal plane, the full FoV (~40 arcmin dia.) is covered by ~400 × 400 pixels, less than a quarter of the pixel array. Therefore, one 512-column processor is sufficient, and only the illuminated pixels/rows need to be read out, greatly reducing the amount of telemetered data, and potentially reducing the required speed of the associated electronics.

**Onboard Data Processing Scheme**

A main challenge for SSAXI is onboard data processing under the large solar X-ray flux. For a 12U CubeSat version with ~2 cm² effective area at 1 keV, the full downlink of observed X-ray event lists may be too large even during quiet solar states (A: ~10^{-8} W m^{-2}). In
order to enable efficient search for X-ray signature of solar axions under the large X-ray flux from the solar disc experiencing regional variations (e.g., micro- and nano-flares), the data will be telemetered in two modes – event and spectral modes with the latter being the main telemetry mode.

Table 2 summarizes the expected data rate of SSAXI during the solar minimum. In the event mode, energies of all 3×3 pixels surrounding each trigger pixel are telemetered. The data rate of the full event mode data is expected to be over multi GBytes per day (e.g., ~10 GBytes per day for 1 kcps), so a small subset (e.g., about 10 mins worth) will be downloaded daily for diagnostic and parameter optimization purpose (e.g., event and charge split threshold, etc.).

For search of X-ray signature of solar axions, the spectral mode is utilized. Since the X-ray signature of solar axions is expected to be more clearly identifiable if both the spatial (i.e., an excess in the solar core over the solar disc) and spectral (i.e., an excess in the 3 – 4 keV band over the broadband) signatures are observed, we first divide the solar disc into about 5000 spatial resolution units (~30–60 arcsec or 5–10 pixel dia. per unit). Then, we accumulate the daily X-ray spectrum of each spatial unit. Based on the activity level of each spatial unit, we accumulate a set of spectra while bookkeeping the matching exposure interval of each level. For instance, four sets of the spectra can be accumulated, corresponding to the solar state levels of sub-A (< ~10⁻⁸ W m⁻²), A (~10⁻⁸ – 10⁻⁷ W m⁻²), B (~10⁻⁷ – 10⁻⁶ W m⁻²), and above B (> ~10⁻⁶ W m⁻²). The on-board process can tally on-going average X-ray counts of each spatial unit over a fixed interval (e.g., 10 min), and the average X-ray count level will determine which level of the spectra will be accumulated from the previous interval. In this way, the low state spectral set will provide the quietest state of the solar spectra over the entire disc in ~30 – 60 sec resolutions, providing the highest chance of detecting X-ray signature of solar axions.

To keep the pile-ups below 1%, the average incident X-rays on the active region of the detector should be limited to about 25 kcps (or 0.2 cps per pixel at 20 Hz readout). A ~250 µm Be window will allow about 1 kcps of solar X-rays incident on the CMOS X-ray sensor at solar A states. The daily 4 × 5k spectra of 20 eV bins over 0.5 – 10 keV would be about 20 MB/day, while the event data of 25 kcps would be about 25 GB/day. The latter can be prohibitively high for SmallSats, as aforementioned. Thus, with a small portion of events for daily diagnostics, the expected total data rate of the spectral mode data for 1 yr science operation is about 14 GB /yr with 70% duty cycle and 20% overhead for HK and data headers (Table 2).

Table 2 Data Rate of SSAXI XIS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
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<tbody>
<tr>
<td>Readout freq.</td>
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<tr>
<td>Pile-up limit</td>
<td>&lt;1 %</td>
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<tr>
<td>Max event rate</td>
<td>25 kcps over ~360 × 360 pixels</td>
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<tr>
<td>Dynamic range</td>
<td>A states with 250 µm Be window</td>
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<tr>
<td>Duty cycle</td>
<td>50%</td>
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<td>Mode</td>
<td>Event</td>
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<td>Spectral</td>
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<tr>
<td>Data type</td>
<td>3×3 pixel energies of each event</td>
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<td></td>
<td>3×5k spectra, 512 bins with 20 eV steps</td>
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<td>Daily duration</td>
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<td>Daily rate</td>
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</tr>
<tr>
<td></td>
<td>20 MB</td>
</tr>
<tr>
<td>Total data rate</td>
<td>14 GB for 1 yr science op</td>
</tr>
</tbody>
</table>

MISSION DESIGN

Mission Implementation

SSAXI can be designed to be a secondary mission to have a rideshare to a sun-synchronous orbit at an altitude somewhere between 600 and 1000 km. Alternatively, it can have a rideshare to a LEO or be released to a LEO from the International Space Station. Sun-synchronous orbits enables uninterrupted continuous observations of the Sun with the XIS in a more stable thermal environment. On the other hand, they are nearly polar orbits, where the instrument can experience higher instrumental background than in LEOs of low inclinations that avoid the South Atlantic Anomaly (SAA). The low inclination orbits, however, can reduce the observing time by more than half due to Earth occultations, which will also force the XIS to...
experience the periodic changes in its thermal environment, thus requiring a more careful design of the thermal system (e.g., NuSTAR observations of the Sun). For search of sterile neutrino, LEOs would be preferable. More in-depth simulations will be required to assess upsides and downsides of each orbital configuration.

Given expected relatively low costs of CubeSat/SmallSat missions, multiple SSAXI missions can be deployed to various orbital configurations, depending on launch opportunities, to establish higher photon statistics, which in turn enhances a chance of detecting X-ray signature of solar axions or provides a stronger constraint on the axion coupling constant.

**SUMMARY**

SSAXI is a SmallSat concept designed to search for X-ray signature of solar axions by capturing X-rays converted from solar axions or ALPs through inverse Primakoff effects. Since the solar core is expected to generate axions or ALPs whose energy peaks at 3 – 4 keV, the converted X-rays will have the spectrum peaking in the similar energy band, and this spectral signature is expected to be more prominent along the line of sight to the solar core. The imaging spectroscopy of the solar disc, therefore, enables unambiguous identification of the X-ray signature of solar axions.

Recent advances in X-ray telescopes and instruments such as Miniature X-ray Optics (MiXO) and monolithic CMOS X-ray sensors enable a compact X-ray imaging spectrometer suitable for CubeSat/SmallSat missions.

**References**


