FOXSI-4: The high resolution focusing X-ray rocket payload to observe a solar flare

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ABSTRACT

The FOXSI-4 sounding rocket will fly a significantly upgraded instrument in NASA's first solar flare campaign. It will deploy direct X-ray focusing optics which have revolutionized our understanding of astrophysical phenomena. For example, they have allowed NuSTAR to provide X-ray imaging and IXPE (scheduled for launch in 2021) to provide X-ray polarization observations with detectors with higher photon rate capability and greater sensitivity than their predecessors. The FOXSI sounding rocket is the first solar dedicated mission using this method and has demonstrated high sensitivity and improved imaging dynamic range with its three successful flights. Although the building blocks are already in place for a FOXSI satellite instrument, further advances are needed to equip the next generation of solar X-ray explorers. FOXSI-4 will develop and implement higher angular resolution optics/detector pairs to investigate fine spatial structures (both bright and faint) in a solar flare. FOXSI-4 will use highly polished electroformed Wolter-I mirrors fabricated at the NASA/Marshall Space Flight Center (MSFC), together with finely pixelated Si CMOS sensors and fine-pitch CdTe strip detectors provided by a collaboration with institutes in Japan. FOXSI-4 will also implement a set of novel perforated attenuators that will enable both the low and high energy spectral components to be observed simultaneously in each pixel, even at the high rates expected from a medium (or large) size solar flare. The campaign will take place during one of the Parker Solar Probe (PSP) perihelia, allowing coordination between this spacecraft and other instruments which observe the Sun at different wavelengths.

Keywords: The Sun, high-energy, X-rays, sounding rocket, X-ray focusing optics

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1. INTRODUCTION

The Focusing Optics X-ray Solar Imager (FOXSI) is the first solar-dedicated NASA sounding rocket experiment that performs imaging spectroscopy in hard X-rays (HXRs) using direct focusing techniques. FOXSI has improved the sensitivity and imaging dynamic range by orders of magnitude compared to its predecessors (e.g., RHESSI), demonstrated in three successful flights (2012, 2014, and 2018)[1–12] to date. For the fourth flight (FOXSI-4), the hardware upgrades focus on implementing higher-resolution X-ray optics, higher photon rate capability detectors, and microfabricated attenuators to optimally reduce count rates. These technologies will be demonstrated in NASA's first-ever (non-micro) solar flare campaign in March 2024. Such a flare campaign will coordinate multiple rocket experiments, FOXSI-4 included, with a Parker Solar Probe (PSP) perihelion crossing the Sun-Earth direction allowing to observe the Sun simultaneously in multiple wavelengths. The FOXSI-4 flight will constitute the first time that a direct focusing hard X-ray instrument observes, in a rather wide energy range, a medium/large solar flare, and will indicate the sort of accomplishments that a solar-dedicated spacecraft based on this technology could achieve in the future.

2. FOXSI-4 NEW CAPABILITIES

The next generation of HXR solar telescopes will demand higher time and angular resolutions to investigate solar smaller-scale structures with complementary observations by solar instruments at other wavelengths. FOXSI is a pathfinder probing new capabilities to meet such requirements (see figure 1). FOXSI-4's new developments encompass two classes: high-resolution imaging for easy separation of sources within flares and high photon count rate capabilities for measuring bright flares. For the first class, FOXSI-4 will use high-precision mirrors coupled with finely pixelated Si CMOS sensors and will implement sub-strip/subpixel resolution in fine-pitch CdTe sensors. For the second class, FOXSI-4 will introduce novel microfabricated attenuators for energy coverage optimization and demonstrate that the sensors' rate capabilities are sufficient for flare measurement. Table 1 summarizes the instrument design parameters for FOXSI-4.

Energy range	2-20 keV (unattenuated) 3-20 keV (attenuated)
Effective area	$\sim$50 cm^2 at 10 keV (unattenuated) $\sim$2 cm^2 at 10 keV (attenuated)
Optics FWHM	$\sim$1" (Nagoya optics) $\sim$2" (MSFC optics)
Optics HPD	$\sim$10" (Nagoya & MSFC optics)
Angular resolution (best) [*] (combined optics+detector)	$\sim$1.8" (CMOS) $\sim$3.6" (CdTe)
Energy resolution	0.17 keV at 6 keV (CMOS) 0.8 keV at 14 keV (CdTe)
CdTe detector photon rate	$\sim$5,000 photons/det/s

Table 1. FOXSI-4 sounding rocket payload projected performance. A future space mission implementing FOXSI's concept with a longer focal length would automatically have a finer resolution even with no changes in the detector parameters.

2.1 Optics improvements

FOXSI has traditionally used monolithic Wolter-I mirrors manufactured at the NASA/Marshall Space Flight Center (MSFC) via an electroformed nickel alloy replication technique.[13–15] The standard MSFC mirror fabrication begins with rough cutting a mandrel from an aluminum block, tapering it, and plating it with electroless nickel. Next, the Wolter figures get shaped by diamond turning the hard overcoat, iterating several times until achieving the desired surface roughness. Subsequently, the mandrel is submerged in a nickel-cobalt bath to produce a final thin shell mirror that separates from the mandrel in a chilled water bath. Such mirrors of various

[*]The best angular resolution reported here is calculated using the optics FWHM and information of charge sharing effects over the CdTe detectors.

radii are coaxially grouped into 7- or 10-shell modules to increase the instrument's effective area. Laboratory measurements show a 4.3 ± 0.6 arcsec full width at half maximum (FWHM) and 27 ± 1.7 arcsec (half-power diameter; HPD) on-axis averaged resolution for a standard optics module (Christe et al., 2016; Krucker et al., 2013).

FOXSI-4 will develop new optics on two fronts: one building on the heritage FOXSI optics produced at the MSFC and another via a novel effort focused on extremely high-resolution optics for X-rays at Nagoya University, Japan in collaboration with the University of Tokyo and Natsume optical corporation. The MSFC will implement a deterministic polishing technique[16] (using Zeeko) and improved shell separation techniques for the optics to achieve a resolution of 2 arcsec (FWHM) and 10 arcsec (HPD), a 2.5 improvement factor over previous FOXSI payloads. For the high-resolution electroformed optics from Nagoya, Nagoya University and their collaborators have already fabricated full-shell X-ray optics. They use a high precision electroforming technique specialized for small ground-based X-ray focusing optics.[17] The expected resolution of the Nagoya optics is 10 arcsec (HPD) and 1 arcsec (FWHM).

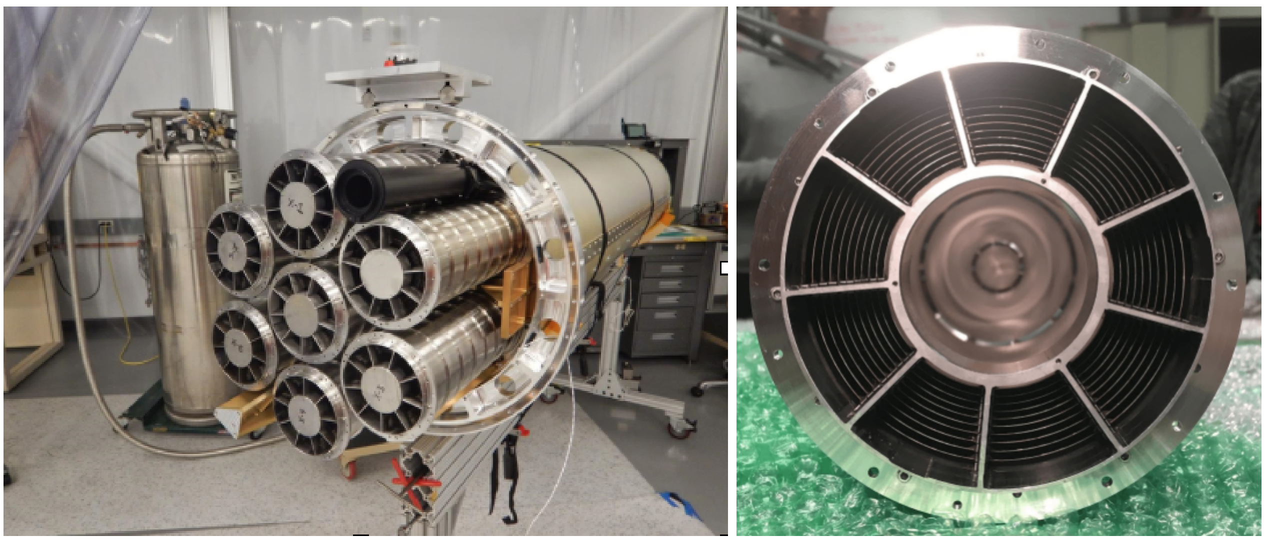

Figure 1. *Left*: Photographs of the optic end of the FOXSI-2 instrument before launch. *Right*: Close-up photograph of the rear end of an optics module nesting 10 Wolter-I mirrors shells that was flown in FOXSI-2 and FOXSI-3.

2.1.1 High-resolution MSFC electroformed optics

Each step in the MSFC optics fabrication process will be improved to attain the desired spatial resolution. A deterministic polishing technique will assure an improved mandrel surface and figure.[18,19] MSFC has already mastered such a technique and demonstrated it with the mandrels for the MaGIXS rocket experiment,[20] utilizing a Zeeko IRP 600X computer-numerical-control (CNC) polishing machine. The MaGIXS mandrels significantly reduced axial slope errors (to 0.72 and 1.26 arcsec HPD on the paraboloid and hyperboloid sections, respectively) for spatial wavelengths > 7 mm after applying the polishing technique several times.[16] For the FOXSI-4 payload, the high optics performance will be enhanced to enable 2 arcsec FWHM by improving the shell formation and separation procedures in four steps: First, two new mandrels will be CNC polished to 1-2 arcsec HPD using the continuously improving MSFC process. Second, the pulse plating procedure will be optimized to reduce the stress in mirror shells during electroforming. Third, the micro-yield strength of the shells will be increased by testing on an improved alloy. Fourth, the mandrel/shell release process will be improved in several ways, including employing interior cooling of the mandrel/shell combination instead of exterior cooling in a water bath, varying the timing of the release process, and investigating the release mechanism using strain gauges to determine the pattern of separation. Additionally, the MSFC will utilize a new physics modeling code using COMSOL to understand better the electric field in the plating bath and find configurations to make the field more uniform, leading to a more consistent thickness and lower stress in the shells. Most of the fabrication protocols follow directly on to the most recent development for MaGIXS (see Kobayashi et al., 2018[20]). The MSFC will deliver three upgraded modules (already produced and calibrated as needed), each containing two high-resolution mirrors, using as much fabrication heritage from FOXSI-3. Two upgraded modules will pair with CdTe (HXR) detectors, and one will pair with a CMOS (SXR) detector.

2.1.2 High-resolution optics from Nagoya

Nagoya University (playing a lead role) has partnered with The University of Tokyo and Natsume optical corporation to produce high-resolution X-ray optics for FOXSI-4. They will apply a high-precision electroforming technique, initially developed to fabricate small ground-based X-ray Wolter-I optics. Such previous optics showed to achieve point spread functions with sizes under 1μm (FWHM).[17] The Nagoya University and collaborators are currently adapting their technology to provide a Wolter-I optics for FOXSI-4. The optics for FOXSI-4 will consist of a monolithic Ni electroformed mirror with a diameter and a length of 60 mm and 100 mm, respectively. The team lead by Nagoya University has already tested FOXSI-4's mirror prototypes, finding minimal figure errors (1-3 um in PV) for the circumferential profiles. This same team will conduct X-ray irradiation tests in the near future. After alignment and calibrations, the goal is to have two single-shell optics modules, each achieving a 10 arcsec HPD and 1 arcsec FWHM.

2.2 Advanced attenuators

With the advent of powerful X-ray focusing optics for solar observations comes the need to control the photon rate such that the detectors do not get saturated. With its first large flare observation, FOXSI-4 demands a strategy to maintain fluxes at a controllable level. Such a level of control will be attainable for FOXSI-4 by implementing uniformly thick aluminum attenuators (inherited from previous FOXSI flights), and novel Microfabricated Pixellated Attenuators (MPAs) designed and built by NASA/Goddard Space Flight Center (GSFC).

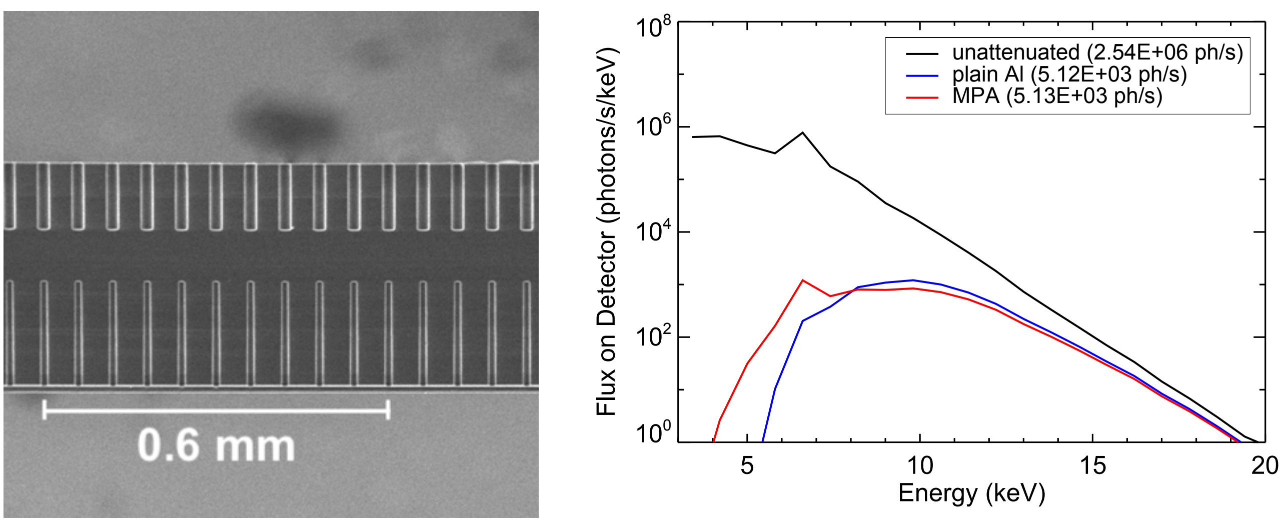

Figure 2. Left: Side photo of a prototype attenuator highlighting structural details of the microfabricated piece. Right: Simulated effect of the advanced attenuators after accounting for the optics energy response and blanketing in the payload. The black curve shows the unattenuated X-ray spectrum incident on a detector from a model coronal source in an M3.5 flare after it is focused by a FOXSI optics module. The incident spectrum is attenuated to a rate measurable by the FOXSI detectors with low deadtime (red curve) but maintains measurement of all the spectral features of interest across the entire energy range (including the 6.7 keV line complex), as opposed to traditional single-thickness attenuators (blue) which would cut off the low-energy spectrum..

Previous FOXSI payloads included an attenuator wheel that could insert simple, uniformly thick aluminum attenuators. Five of the FOXSI-4 detectors will use such an attenuator scheme, a fixed (immovable) aluminum window and an insertable attenuator (on a wheel) optimized to limit rates to ~5,000 photons/detector/sec for a C5 and M3 flare, respectively. The existing ability to monitor rates and command the attenuator from the ground will straightforwardly accommodate a range of flare brightnesses.

Traditional attenuators tend to overly dampen the instrument's low-energy response. FOXSI-4 will debut a novel solution to this issue via the advanced MPAs on two of its telescope modules. The MPAs are being developed by GSFC specifically for pixelated spectroscopic X-ray detectors and can preserve sensitivity between 3-20 keV in a moderate to large flare. MPAs are fabricated by etching small holes in silicon wafers at the same pitch as the detector using a microlithography process (see Figure 2). These MPAs allow a small fraction of low-energy X-rays to reach each pixel without introducing a positional dependency to the detector response. Additionally, the MPAs can be stacked to achieve greater thicknesses with a small hole diameter, and the silicon wafers can be coated with other materials, e.g., gold, for achieving specific attenuating properties.

As an example, an unattenuated spectrum for an M3.5 class flare can easily reach > 3 million photons s^{-1} (black curve in Figure 2); to attenuate this flux, one can use a simple 230 μm wafer of Si (blue curve in Figure 2). However, this substantially reduces the counts below ~6.5 keV, including part of the emission line complex. We can achieve the same reduction in count rate using a 480 μm thickness MPA with a hole diameter of 6 μm (red curve), but preserving the low energy signal for more reliable spectral fitting. Most notably, the entire emission line complex at 6.7 keV is retained.

The MPAs absorb X-rays at low energies but transmit those at high energies. The small open areas they include over each detector segment help retain effective areas at even low energies. The result is a relatively flat effective area curve, allowing FOXSI to be sensitive across its energy range without being swamped by steep solar flare spectra.

The GSFC will design several attenuators for different flare sizes. The flight versions will be chosen before launch based on estimates of target flares by the flare campaign scientific group. In addition to the MPAs, insertable slab attenuators will additionally reduce low-energy flux in the case of a large flare.

2.3 Detector improvements

The detector plan includes upgrades to two heritage detectors - double-sided CdTe strip detectors for HXRs and Si CMOS sensors for SXRs - but also includes the debut of a pixellated CdTe sensor using the Timepix ASIC that has never before been used for solar physics applications. The following sections describe each of these developments.

2.3.1 CdTe strip detectors

FOXSI will implement improved CdTe double-sided strip detectors with a higher yield, finer position resolution, and higher count rate capabilities for its fourth flight. Such detectors will use strip pitches of 60 μm and enable sub-strip resolution due to an optimized electrode structure. These devices will utilize the application-specific integrated circuit (ASIC) already developed for FOXSI-3[9](Figure 3) and the Hitomi Soft Gamma-ray Detector (SGD) and upgraded FPGA-IP optimized for high-speed readouts of 5 kHz per detector (10 times faster than FOXSI-3) to support the higher count rate of solar flares. FOXSI's double-sided CdTe strip detectors are provided by Kavli IPMU and JAXA/ISAS. These detectors, sensitive to hard X-rays above ~5 keV, will be upgraded for a net 10x improved count rate and the higher spatial resolution achievable via the use of charge sharing information.

2.3.2 CdTe pixelated detectors (Timepix)

FOXSI-4 will debut for the first time the use of a novel CdTe pixelated detector with a Timepix3 readout for solar observations. The Timepix3 is a 256×256 hybrid pixelated readout ASIC bump bonded to a 1 mm thick CdTe sensor with a 55μm pixel size[21] (Figure 3, right). The international Medipix collaboration hosted by CERN3, of which the University of California Berkeley's Space Sciences Lab (UCB/SSL) is a member, has been responsible for developing the Timepix3 based detector. The ASIC has two readout modes: data-driven and frame-based. In the data-driven mode, the readout system produces a data packet with energy measurements (time over threshold), time of arrival, and pixel I.D., directly after a photon hits a pixel. Crucially, during this process, the rest of the pixels are still sensitive, allowing for the collection of many photons in different pixels near-simultaneously. The ASIC clocks at 40 MHz with a 640 MHz voltage controlled oscillator allowing up to 40 Mhits/s/cm^2, and a minimum time step for the arrival time of 1.56 ns.[22–25] A single Timepix3 unit consumes 2W of power, which can be reasonably accommodated within the FOXSI-4 power budget. Using a Si sensor bonded to a Timepix3 ASIC, the energy resolution at room temperature and 100V bias voltage has been measured to be 0.72 keV FWHM at 10.5 keV in data-driven mode. Energy resolution measurements down to 2 keV have been made,[22] demonstrating the low-noise performance of the ASIC. Fabrication and characterization of a Timepix3 with CdTe sensors (instead of Si) are currently in progress under the lead of UCB/SSL. That development will produce the first detector that will fly in FOXSI-4. Details of the Timepix3 can be found in publications by Frojdh et al. (2015),[22] Gaspari et al. (2014),[26] Kruth et al. (2010),[23] for example.

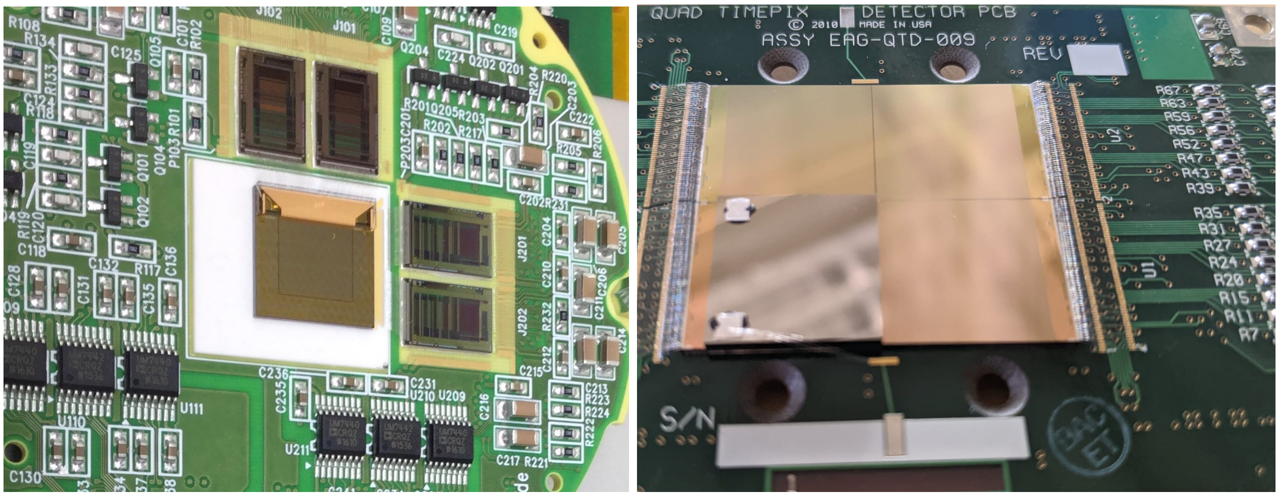

Figure 3. *Left*: Photo of a double sided CdTe strip detector. The strip pitch is 60μm. For more information see Furukawa et.al., 2020.[27] *Right*: Photo of a pixelated Timepix3 detector.

2.3.3 Charge-sharing in CdTe sensors

Charge sharing occurs when the cloud of charge carriers released by a photon impact extends across multiple detector strips, conducting to record a single photon as multiple lower-energy events in adjacent strips. Recently, several teams (e.g., Dreier et al., 2019;[28] Khalil et al., 2018[29]) have performed experiments to achieve subpixel resolution with Timepix3 detectors. Charge sharing has also been implemented to demonstrate sub-strip-pitch resolution in FOXSI detectors[9] using a collimator with 50 μm pinholes to achieve an X-ray beam smaller than the strip. More recently, tests performed by the FOXSI-3 team utilizing a 2μm$\times$2μm controllable monochromatic X-ray beam between 4-15 keV at the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory (LBNL) have measured charge-sharing properties of the FOXSI-3 detectors at 5 μm steps.[30]

2.3.4 Back-illuminated, thick CMOS sensor

The FOXSI-4 experiment also will include a soft X-ray CMOS sensor that flew on the rocket's third flight for the first time and produced the first photon-counting soft X-ray image of the Sun (Figure 4).[31] For FOXSI-4, the CMOS sensor will operate with two times faster readout for the flare campaign and with a thicker sensitive layer for higher energy coverage. Its 1.1 arcsec angular resolution will allow for full utilization of the optics' high-resolution capabilities. The CMOS sensor is provided by the National Astronomical Observatory of Japan, with optical blocking filters provided by Nagoya University.

2.4 FOXSI-4 readiness for rocket flare campaign

FOXSI-4 is ideally suited for NASA's first-ever solar sounding rocket flare campaign because

1. it is a well-established re-flight,

2. it has a wide field of view (FoV) to encompass the entire flare (and/or eruption), and
3. it provides input on the solar sources of non-thermal electrons observed by Parker Solar Probe (PSP).

One already identified possible trigger for the launch is the GOES SXR flux crossing a predefined threshold, but the scientific team will identify other triggers for a robust early flare alert system. It is expected that FOXSI-4 will begin to observe ∼10 min after the flare start (including a few min to reach the GOES threshold) or 5 min after the trigger is identified. The scientific team will explore ways of reducing these times via monitoring active region complexity and dynamics during the days previous to the rocket launch. FOXSI's field of view (FoV) is ∼ 1/4 solar disk, so alignment requirements are not strict. Guarding against the case that the flare occurs in a different region than expected, FOXSI can perform a search of the entire Sun in less than a minute. This information could even be used to inform other campaign experiments with smaller FoVs.

3. SCIENCE OF FOXSI-4

Previous flights of FOXSI developed direct HXR focusing for solar purposes using an angular resolution of the optics limited to 5 arcsec (FWHM) and 25 arcsec (HPD). The development of higher resolution direct solar imagers would revolutionize the study of accelerated electrons in flares. Future, space-based HXR instruments could perform detailed spectroscopic study of coronal acceleration sites, both in and above looptops. Current performance could already separate coronal and footpoint sources (typically tens of arcsec separation) and could separate coronal and high coronal sources. However, the majority of flares have thermal and non-thermal sources in the corona that are separated by <5 arcsec (e.g. Krucker and Lin, 2008[32]), requiring optics resolutions better than that to resolve them. In addition to studying particle acceleration, high-resolution capability would also enable a clear characterization of the source of superhot plasma (>30 MK).[33] As accelerated electrons propagate down flare loops, they collisionally deposit energy and undergo evolution due to several effects, including scattering, turbulence, and return currents (e.g. Alaoui and Holman, 2017;[34] Holman et al., 1982;[35] Miller et al., 1997[36]). Meanwhile, upflows of hot plasma from the chromosphere transform the thermodynamics of the flare loops. Current performance could study the looptop and footpoints separately, but high-resolution capability would enable study of the accelerated electrons at several locations along their propagation paths, better determining which of the many propagation factors are at work.

Past studies have found close correlations between HXR and white light flare footpoints and ribbons.[38,39] RHESSI's best resolution (2.3 arcsec) was sufficient to recognize that HXR and white light ribbons had similar shapes and positions, but RHESSI lacked the dynamic range and sensitivity to observe HXR sources all along the ribbons.[40] The correspondence between HXRs and flare ribbons has large consequences for studies of the evolution of energy release along the arcade and for how energy is transferred into heating of the lower atmosphere. While resolving a single footpoint would require resolution (<1 arcsec) that is still out of reach, imaging at RHESSI-scale resolution (2-3 arcsec) but with good sensitivity and dynamic range would reveal whether HXRs are present along the entire ribbons and at all white light footpoints. This would particularly enhance the science that could be performed with HXRs and the Daniel K. Inouye Solar Telescope (DKIST; about to begin operation[41]), studying the response of the lower solar atmosphere to electron beams.

HXR studies of flare-accelerated electrons are ideally complemented by observations at soft X-ray (SXR) and extreme ultraviolet (EUV) wavelengths. High-resolution (1–2 arcsec) SXR spectral information would pinpoint the locations of reconnection-related heating and of energy deposition by accelerated electrons, as well as characterize their thermal properties.

An example of attainable X-ray resolution is shown in Figure 4. EUV and SXR thermal measurements would reveal the fine details of the flaring loops, elucidating the plasma structures within which the accelerated electrons propagate. Connecting (and pushing the resolution) in all of these wavelengths will lead to unprecedented energy distribution diagnostics that differentiate heated plasma from regions with non-thermal accelerated electrons. We note that two of the three regimes (HXRs, SXRs) can be provided by FOXSI -4 alone, while the third (EUV) can be provided by the Hi-C FLARE sounding rocket experiment, which will flight almost-simultaneously with FOXSI-4.

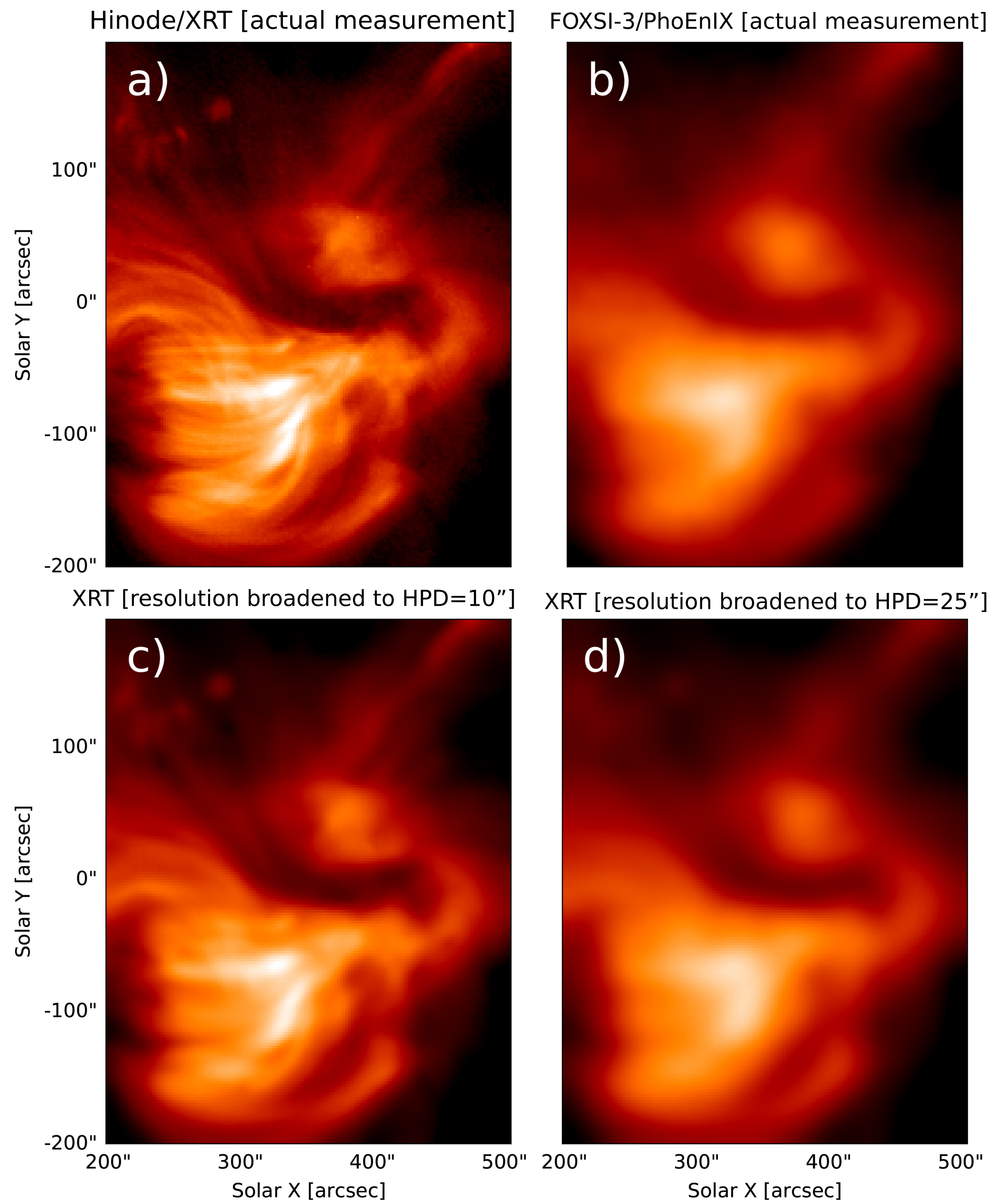

Figure 4. XRT thin-Be (panel a) and FOXSI-3/PhoEnIX (panel b) images of the same region on Sept 7, 2018. To make the XRT thin-Be image, we averaged a total of 93 (non-continuous) observation files taken by Hinode along the 17:00:00 UT - 18:00:00 UT hour, each with 16.4 seconds observation time. The PhoEnIX image was generated using continuous observations of that solar region for 197.2 seconds during the FOXSI-3 flight in the 0.5 - 2.5 keV energy range. The XRT image has 2 arcsec (HPD) resolution[37] but offers no detailed spectral information, while the image from PhoEnIX (as flown on FOXSI -3) gives energies for every photon with an HPD of 25 arcsec. We have convolved the original XRT image with single Gaussians to produce images with equivalent HPDs of 10 arcsec and 25 arcsec, that we show in panels **c** and **d** respectively. The XRT image in panel **c** represents the target angular resolution for FOXSI-4, while the XRT image in panel **d**, and FOXSI-3/PhoEnIX in **b**, show the resolution available with past (FOXSI-3) spectroscopic X-ray imagers. The anticipated improvement in resolution from FOXSI-3 to FOXSI-4 is represented by the progression from panel **b** to panel **c**.

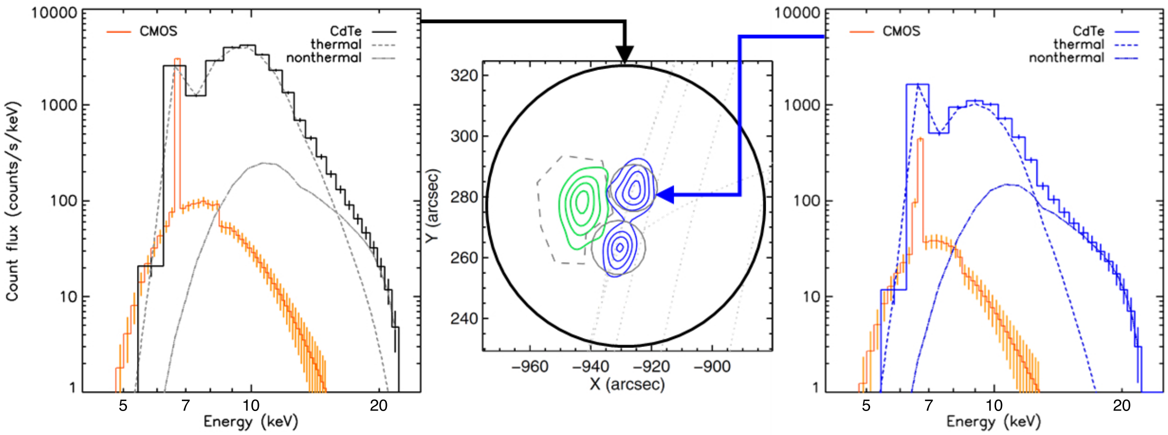

Figure 5. Simulation of a FOXSI-4 observation for 1-second integration of an M3.5 flare observed by RHESSI on Feb 24, 2011.[42] The response includes (blue/black) a CdTe detector paired with a 2-shell high-resolution MSFC optic module and a 260 μm thin aluminum filter, and (orange) a CMOS sensor paired with a one-shell high-resolution Nagoya optic module and a 180 μm thin aluminum filter. Left: spatially integrated spectra. Right: footpoint spectra. While the non-thermal tail of the spectrum is difficult to observe in the spatially integrated spectrum for events in/above M-class,FOXSI can produce a spectrum of footpoints alone, where the non-thermal component can be well characterized.

Non-thermal bremsstrahlung emission often takes the spectral form of a power law. Spatially integrated X-ray flare spectra are dominated by thermal emission at energies $\leq$15 keV, masking the spectral transition due to the low-energy cutoff, leading to a large uncertainty on non-thermal energy content. However, FOXSI-4's imaging spectroscopy allows spectra to be produced in locations where the thermal emission does not dominate, such as the footpoints of coronal loops, as shown in Figure 5. FOXSI-4's non-thermal diagnostics with its SXR imaging spectroscopy and the hot thermal diagnostics of Hi-C FLARE will enable a detailed budget of the energy divided amongst accelerated electrons, heated flare plasma, and the erupting CME or jet (if one occurs). Non-thermal emission is most commonly observed in the flare impulsive phase. In many flares, the HXR emission from accelerated electrons closely matches the derivative of the SXR thermal flux (the "Neupert effect"; e.g. Effenberger et al. (2017);[43] Veronig et al. (2002)[44]), due to collisional energy deposition. We therefore define an impulsive phase as the time from the GOES flare start to peak; in this phase we expect the strongest HXR emission. Figure 6 shows impulsive phase durations vs flare size for Solar Cycles 23 and 24; the plots show (top) the duration of the impulsive phase and (bottom) the fraction of flares for which the impulsive phase lasts longer than 10 minutes for flares of various GOES classes. Larger flares have longer impulsive phases, with $\sim$40% of C5 and $\sim$55% of M5 flares having impulsive phases >10 min (the current expectation for the lag between the flare start and observation start). It is therefore possible, but not certain, that FOXSI-4 will observe during the impulsive phase.

Concretely, FOXSI-4 will work toward the following scientific goals:

- Determine the amounts and locations of energy release throughout solar flares.
- Determine how superhot plasma arises.
- Understand the interaction between accelerated particles and solar ejections.
- Determine how flares accelerate particles and how flare-accelerated electrons transfer energy to the lower solar atmosphere.
- Measure the energetic input of impulsive heating to the corona.
- Establish the practice of flare observation using sounding rocket experiments.

Possibly not all scientific objectives will be fulfilled for a given single flare, but the range of science ensures completion of some objectives regardless the flare type. If the impulsive phase is missed, FOXSI will make high-sensitivity measurements of particle acceleration and plasma heating in the decay phase, which could contain large amounts of energy.

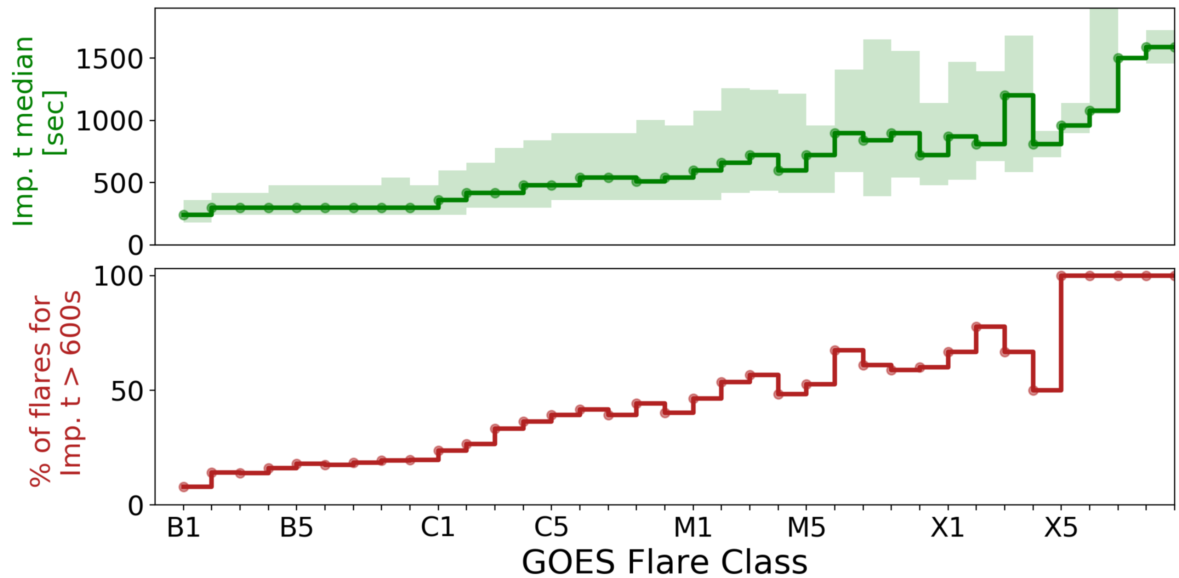

Figure 6. (Top) Impulsive phase durations vs flare class, with (green line) the median duration and (shaded) 25%–75% percentile range shown. (Bottom) Percent of flares with impulsive phases >10 min. ∼40% of C5 flares and ∼55% of M5 flares meet this criteria and would thus have impulsive phases observable to FOXSI-4.

With improved resolution, we can isolate the footpoint spectrum to better characterize the nonthermal component. While FOXSI does not need to observe the impulsive phase to meet its objectives, maximum science return will be achieved if it does.

With FOXSI-4, we seek to work toward the next generation of solar HXR instrumentation by developing better angular resolution and high-rate capability, as well as applying FOXSI 's direct imaging in conjunction with other next-generation solar instruments to study a large solar flare. This work will shed light on the earliest observable high energy signatures that help drive solar eruptions.

FOXSI-4 will support the science achieved with the PSP by providing high-sensitivity X-ray spectroscopic observations of flare-accelerated electrons. Some of these electrons are linked to the energetic populations that PSP observes. Characterizing non-thermal electrons at the flare site with FOXSI-4 and in situ with PSP will help us understand how they escape the low corona and how their distribution evolves as they transit through the heliosphere.

3.1 Solar flare campaign: A new capability for NASA

NASA solar sounding rockets typically launch from the White Sands Missile Range (WSMR), which is severely limited in launch window flexibility due to road closures on the base, a nearby highway, and a national park, with a 1-hour window scheduled months in advance. Triggered observations cannot be performed under these conditions, so all solar sounding rockets to date have only targeted quiescent solar conditions. A recent initiative driven by the sounding rocket community calls for a flexible launch to observe a solar flare, with multiple payloads launched together or in near succession. This is similar to the approach taken for auroral campaigns, in which payloads remain launch-ready on the rail for multi-day intervals until a predefined scientific trigger condition is reached.

A recent white paper[45] outlines a concept for a 2-week flare campaign (initially proposed for March 2023 and now funded for March/April 2024) with a 4-hour launch window each day, with signatures of endorsement from

>30 solar scientists. This concept has a 98% / 64% / 44% chance of observing a flare of GOES class greater than C1 / C5 / M1. The schedule targets the March/April 2024 PSP perihelion in order for the study of the flare/eruption to be complemented by unique in-situ data, resulting in never-before-observed flare measurements using cutting-edge instruments. It is assumed that most or all solar observatories will coordinate with this campaign, making the target flare the most completely observed flare ever. Particularly, by the time of the flare campaign, Solar Orbiter[46] will be close to the Sun-Earth direction, allowing complementary observations from instruments like STIX.[47,48] Poker Flat Research Range (PFRR) has been identified as the launch site for the solar flare campaign.

A flare campaign working group is already formed, including experiment team members and scientists from the broader flare community. This group is advising on scientific plans for the campaign to maximize scientific return. One already-identified possible trigger for the launch is the GOES SXR flux crossing a predefined threshold, but other triggers are being identified by the working group. As detailed in the white paper, it is currently expected that observations can begin ∼10 min after the flare start (including a few min to reach the GOES threshold), or 5 min after the trigger is called. Active region (AR) complexity and activity will be monitored each day to determine targets. FOXSI's FoV is $\sim \frac{1}{4}$ solar disk, so alignment requirements are not strict. Guarding against the case that the flare occurs in a different region than expected, FOXSI can perform a search of the entire Sun in less than a minute. This information could even be used to inform other campaign experiments with smaller FoVs.

3.1.1 Coordination with Parker Solar Probe

The flare campaign is planned for a perihelion and Earth conjunction of PSP, which carries instruments sensitive to accelerated electrons in three ways: electromagnetic (radio) measurements of Langmuir waves, Type II and III bursts (FIELDS), in-situ measurements of particles (ISOIS, SWEAP), and in-situ measurements of plasma waves generated by passing electron beams (FIELDS). All of these diagnostics will be leveraged in coordination with FOXSI-4 data, enabling the study of flare-accelerated electrons from their origins at the Sun through the heliosphere (to the distance of PSP and beyond). One of PSP's primary mission goals is to explore mechanisms that accelerate and transport energetic particles;[49] FOXSI will provide direct input toward this goal.

3.1.2 Solar cycle

The flare probabilities in the white paper[45] assume a solar cycle similar to the previous one. If the next cycle were to be weaker, then the probabilities would be lower, but the chance of at least a C flare remains high. In the unlikely case that activity is so reduced that a flare is not likely to be observed, this would be evident in advance, giving NASA ample time to consider alternative launches. FOXSI-4 will be capable of observing at quiescent times and investigating flare-temperature plasma in active regions (to assess impulsive heating of the corona) and searching for hard X-rays in the quiet Sun as signatures of nanoflares, the same scientific goals as previous FOXSI payloads. The major technological goal of achieving the high angular resolution capability necessary for future HXR measurements will still be achieved.

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