The Focusing Optics X-ray Solar Imager (FOXSI)

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Executive Summary

Particle acceleration on the Sun is one of the main unsolved problems in heliophysics. Accelerated electrons moving through a plasma radiate hard X-ray (HXR) emission through the well-known process of bremsstrahlung. HXR observations therefore provide quantitative measurements of energetic electrons accelerated by the Sun. Present-day HXR instrumentation does not have the sensitivity to see faint HXR emission from electrons accelerated in the corona, nor the dynamic range to see faint emission in the presence of bright HXR flare footpoints. Existing observations therefore show us only where energetic electrons are stopped, but not where they are accelerated, nor along what path they escape from the acceleration site. The next breakthrough in understanding solar particle acceleration requires that electrons be imaged directly in the corona with good spectral resolution. New HXR focusing optics combined with position-sensitive solid-state detectors with ~1 keV spectral resolution can now provide these measurements. This white paper presents a mission concept for the Focusing Optics X-ray Solar Imager (FOXSI). This future instrument will tell us where electrons are accelerated, along which field lines they travel away from the acceleration site, where they are stopped, and how some electrons escape into interplanetary space, with simultaneous spectral information of the accelerated electrons.

Introduction

The Sun is the most energetic particle accelerator in the solar system, producing ions up to tens of GeV and electrons to tens of MeV. Large solar flares are the most powerful explosions in the solar system, releasing up to $10^{32} - 10^{33}$ ergs within $10^2 - 10^3$ s. The accelerated $10 - 100$ keV electrons (Lin & Hudson 1976; Emslie et al. 2005) and sometimes 1 MeV/nucleon ions contain up to 50% of the total energy released indicating that particle acceleration and the energy release processes are intimately linked. CMEs, another form of solar eruptive event, release a significant fraction of their energy in accelerated particles as well (see, e.g. Mewaldt 2006). While it is known that impulsive solar energy release is powered by magnetic energy, the energy release and particle acceleration processes are not yet understood. Hard X-ray (HXR) spectroscopic imaging observations provide sensitive quantitative measurements such as the energy spectrum, density, location, and energy content of accelerated electrons. HXR observations, therefore, hold the key to understanding the particle acceleration mechanism present in solar impulsive energy release.

So far, propagating electrons are rarely observed in the corona through their coronal HXR bremsstrahlung signatures though this is where they are thought to be accelerated by many types of solar impulsive energy release such as flare, CMEs, radio bursts (type I, type III, etc.) and jets. This is due to limitations in current HXR spectroscopic imagers. The purpose of this white paper is to describe a new instrument concept, called FOXSI. Short for the Focusing Optics X-ray Solar Imager, FOXSI will enable the next breakthrough in understanding particle acceleration by providing up to two orders of magnitude greater sensitivity and dynamic range compared to previous instruments. **FOXSI will observe energetic electrons directly in the corona where they are accelerated.**

FOXSI Science

Flares
According to the standard model of solar flares, particle acceleration occurs at or near the magnetic reconnection side in the corona. While details of the standard model are still open to question, multiple observations support the existence of a coronal acceleration region such as timing studies by Aschwanden et al. (1995) and, more recently, observations of paired coronal thermal sources (Sui and Holman 2003), and statistical studies of partially disc-occulted flares (Krucker & Lin 2008).

One of the most iconic examples of coronal acceleration is the Masuda flare (see Figure 1), which shows a coronal nonthermal HXR source distinct from the flare
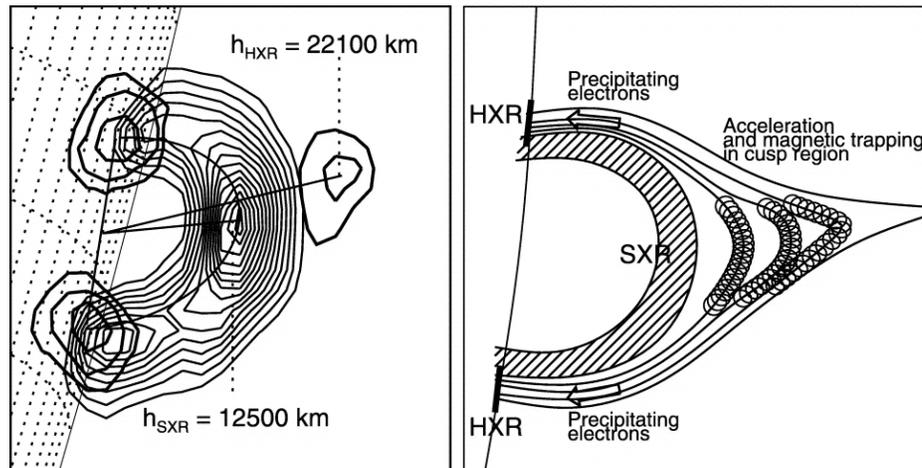

Figure 1: The Masuda flare. (Left) HXR Observations of the Masuda flare (1992 January 13 1728 UT) which show a Yohkoh HXT 23–33 keV image (thick contours) of two footpoints and an above-the-loop HXR source interpreted as the acceleration region itself. Be119 SXT image (thin contours) outline the thermal loops (Masuda et al. 1994). (Right) The standard flare model interpretation of the Masuda flare. Figure from Aschwanden 2004.

footpoints (Masuda et al. 1994). Masuda-type observations are currently very rare though coronal sources in partially occulted flares are ubiquitous, found in ~90% of cases studied (Krucker & Lin 2008). This is because coronal HXR sources are generally faint compared to the bright HXR footpoints. Similarly, thermal emission from the footpoints is lost in the limited dynamic range of the much brighter thermal source seen in the corona. The study of the coronal acceleration region is currently limited to cases which display extraordinarily high coronal HXR intensities or have occulted footpoints. A comparison of partially occulted and non-occulted events show that fluxes at 30 keV are 10 to 100 times larger when the footpoints are visible. Current instrumentation has a dynamic range limited to 10 and thus cannot often image coronal sources and footpoints together. **New grazing incidence HXR focusing optics can now provide the necessary dynamic range and sensitivity to always observe coronal HXR sources even in the presence of bright footpoint emission.**

Detailed measurements of coronal bremsstrahlung HXR spectral parameters and their evolution will constrain flare particle acceleration mechanisms. Coronal HXR sources can give direct information on the energetic electrons in the corona such as their spectra, energy content, and location, as they are being accelerated. Observations of simultaneous footpoint and coronal HXR sources will allow us to understand the transport effects at work (e.g. return currents, wave-particle interactions) as electrons travel from the acceleration region to the footpoints. Coronal trapping can be investigated by examining the evolution of coronal HXR spectra, which should harden due to the shorter collisional loss times of lower-

energy electrons. Combined with knowledge of coronal densities provided by radio emission, EUV, or SXR observations can determine the instantaneous number of accelerated energetic electrons and the energetics of the acceleration process as a function of time. Hence **FOXSI will provide quantitative measurements of the population of accelerated electrons within the acceleration region itself.**

Radio-producing Electrons

HXR emission is also expected from electrons that produce coherent radio bursts seen in meter and centimeter wavelengths (Bastian et al. 1998). Radio emission is frequently associated with escaping electrons such as radio type III bursts or type II radio bursts associated with C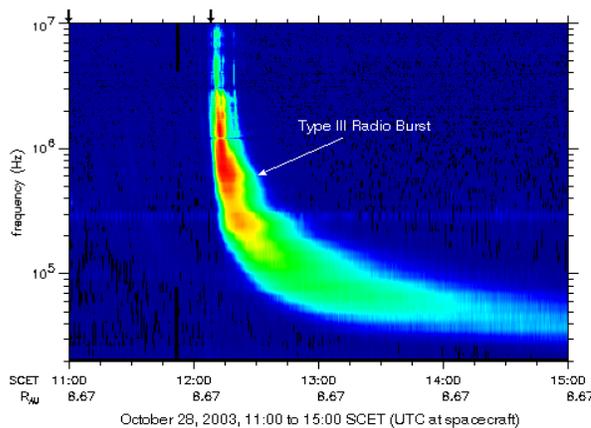ME shocks (see next section). Type III bursts are thought to be produced by beams of escaping electron traveling through the corona. Observed in plasma emission generated at the local plasma density, they are frequently associated with solar energetic particles (SEPs) detected at Earth. Radio observations provide unparalleled sensitivity to detect these events near the Sun yet they do not provide quantitative information about these electrons. Although these beams generally travel in low densities, they also radiate in HXRs, albeit at a much lower rate than

Figure 2: Type III Radio burst. Frequently associated with flares, radio type III bursts are associated with beams of escaping electrons.

downward moving flare beams (Saint-Hilaire et al. 2009). The HXR observation of a type III beam is therefore difficult for two reasons: relatively small fluxes and the large dynamic range necessary since such bursts are often associated with flares. The HXR flux of an escaping electron beam consisting of 10^{33} electrons above 5 keV, consistent with *in-situ* electron measurements near 1 AU (Lin et al. 1973), propagating away from the Sun can easily be detected by FOXSI (Saint-Hilaire et al. 2009). **FOXSI will, for the first time, provide quantitative information about the energy content and spectra of escaping electrons events (SEPs) directly at the Sun.** This could then be compared with particles observed at Earth in order to understand the transport processes active between here and the Sun and the acceleration mechanism itself.

CMEs and SEPs

Coronal mass ejections are known to drive interplanetary (IP) shocks and are frequently associated with powerful flares that accelerate particles to high energies. These shocks are frequently associated with type II radio bursts produced in the corona and IP medium. Solar energetic particles (SEPs) are frequently associated with type II radio bursts providing strong evidence that these shocks accelerate

particles. Similar to flares, CME-driven shocks are very efficient particle accelerators with up to 10% of the CME's total energy being converted to SEPs (see, e.g. Mewaldt 2006). Though IP shocks are frequently detected *in-situ* at Earth, they have already evolved and do not reflect the properties present at the Sun where most of the particle acceleration is thought to occur. Radio observations are currently the best way of observing these electrons near the Sun yet cannot give detailed information about the energetics of these accelerated electrons. In addition, type II radio bursts are only sensitive to electrons in the energy range of 0.2 to 10 keV (Bale et al. 1999). FOXSI observations of shock-accelerated electrons in the low corona would provide unprecedented information about these electrons before they arrive at Earth such as their spectra and location. **FOXSI observations will allow us understand how shocks accelerate particles and the conditions necessary for shocks to be efficient accelerators.**

Coronal Heating and Quiet Sun network flares

The energy released by flares is one of the proposed mechanisms to explain the million degree solar corona (i.e, the coronal heating problem). Large- and medium-sized flares are well observed but are known to produce insufficient amounts of energy to heat the coro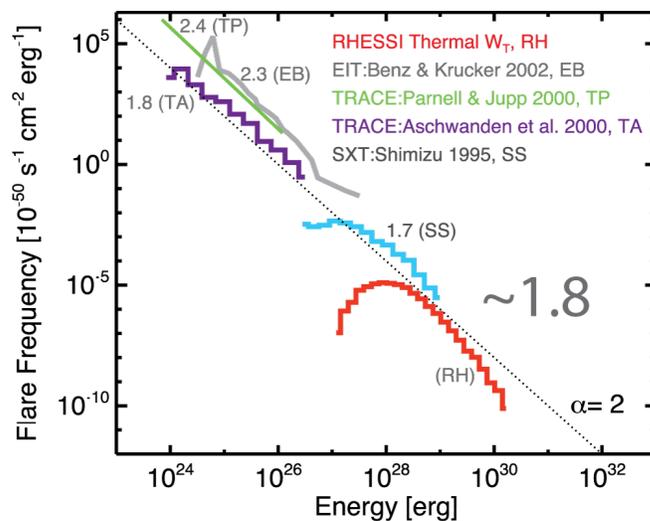na (Crosby, Aschwanden, & Dennis, 1993). Parker (1988) has suggested that a likely candidate to explain coronal heating is continuous flaring at small scales, so-called nanoflares. Therefore, there is great interest in studying the smallest observable events in order to ascertain whether small flares can be responsible for the high temperature of the solar corona.

Figure 3: The flare frequency distribution. *The smallest observed flares have only been measured in thermal emission in the EUV by instruments such as TRACE and SOHO/EIT. These events are observed outside of the active regions, in the quiet Sun. Their slope have significant uncertainty. At higher energies, flare energies are more certain because estimated from thermal or nonthermal HXR emission. FOXSI observations of the smallest events would answer whether the quiet Sun flares are the same as larger flares and whether they heat the corona.*

RHESSI, with 100 times the sensitivity of previous mission at 10 keV, has detected nonthermal emission from microflares from active regions in the 3-15 keV range. The nonthermal energy content in these HXR microflares is derived to be down to 10^{26} ergs, showing that previous studies have underestimated the energy content in small flares (Benz and Grigis 2002; Krucker et al. 2002). However, the total

energy of these microflares is still not enough to account for coronal heating (Christe et al. 2008; Hannah et al. 2008).

The smallest observed events have only been seen in thermal soft X-rays and EUV outside of active-regions in the so-called quiet corona (Krucker et al. 1997; Krucker & Benz 1998; Aschwanden et al. 2000; Parnell & Jupp 2000; Benz & Krucker 2002). These events are referred to as network flares, even though it is has not been established that they are similar to normal flares observed in active regions. The current sensitivity of RHESSI is not good enough to detect these events in the quiet corona (Christe, Krucker and Lin 2008, Hannah 2008). **The large sensitivity provided by FOXSI will, for the first time, make it possible to search for nonthermal HXR emission from network flares.**

Radio observations have revealed the existence of nonthermal electrons in some network flares (Krucker et al. 1997), suggesting that network flares are heated in a similar way to regular flares occurring in active regions. If network flares are indeed smaller versions of regular flares, the thermal heating seen in EUV and SXR is due to nonthermal electrons. Since network flares are only heated to temperatures below 2 MK (Krucker et al. 1997), HXR emission above 3 keV is expected to be dominated by nonthermal emission. The absence of nonthermal emission would clearly establish that the brightenings in the quiet corona are not associated with accelerated energetic electrons. **FOXSI will determine whether brightenings in the quiet corona are similar to active region flares and whether they are the cause of the million degree corona. In addition to the search for nonthermal emission, FOXSI will be able to search for faint high temperature (>5 MK) coronal plasma which may be another signature of the coronal heating process.**

FOXSI Instrumentation

RHESSI HXR measurements are obtained with non-focusing rotation modulation collimator (RMC) imaging technique (Hurford et al. 2002). RMCs and other types of non-focusing imaging, however are limited in three ways: (1) limited effective area, (2) large non-solar background, and (3) limited dynamic range (defined as the ratio of strongest to weakest observable source) due to indirect imaging. Newly developed HXR grazing-incidence focusing optics can overcome all of these limitations.

Rotating modulator collimators as used in RHESSI and other types of non-focusing imaging have the disadvantage of a dynamic range limited by the entire field of view. Even for large flares, RHESSI's dynamic range is <30, making it difficult to see faint and bright sources simultaneously. For microflares, the dynamic range is still lower (<5) due to low counting statistics. For focusing optics, the dynamic range (and resolution) is set by the shape of the point spread function (PSF), the more peaked the PSF the better the dynamic range. Currently, the dynamic range of metal

HXR focusing optics for sources separated by 25 arcsec (a typical separations between footpoints and coronal sources), is >50. Furthermore, calibration will allow for the observed images to be deconvolved, further increasing the dynamic range to >100 for events with good statistics. For well-separated sources, the dynamic range is even larger, up to ~1000.

Indirect imaging provides effective area that is proportional to physical detector area. High sensitivity can then only be achieved through large detectors yet such detectors are difficult to shield against non-solar background. New solid state detectors (e.g. Si, CdTe, CZT) can now provide high quantum efficiency in the HXR range with pixel sizes perfectly suited for FOXSI (≤500 μm). Compared to RHESSI, the area sensitive to non-solar background for FOXSI is $\sim 10^{-6}$ times smaller. Combined with active-shielding, negligible non-solar background can be expected. Event detection then requires >10 times fewer counts than RHESSI for the same effective area.

Figure 4: **The point spread function** *for a single HERO telescope module compared to other similar X-ray instruments. RHESSI is the only non-focusing system and the only solar instrument in the HXR range. The measured point spread function for a FOXSI module is also shown with the expected FWHM of 8 arcsec and an HPD of 25 arcsec.*

HXR optics typically provide ~3 cm² of effective area per kg. Therefore, FOXSI with a mass comparable to RHESSI (130 kg), a Small Explorer class mission, would provide close to 400 cm² of effective area nearly 7 times that provided by RHESSI. **FOXSI will be more than 100 times more sensitivity than RHESSI.**

Current and future FOXSI

In preparation for a future satellite-based mission, FOXSI is currently being developed as a sounding rocket payload (Krucker et al. 2009). With a launch date at the end of 2011, the FOXSI sounding rocket has a focal length of only 2 m and an energy range of 1 to 20 keV. Based in large part on technologies developed for the High Energy Replicated Optics (HERO) balloon payload and the Hard X-ray Telescope (HXT), part of the JAXA mission, Astro-H, FOXSI is the first mission which applies HXR focusing optics to solar observations. Making use of silicon strip detectors (to be replaced by CdTe for its second flight), FOXSI will make the first observations of nonthermal electrons in network flares occurring in the quiet Sun.
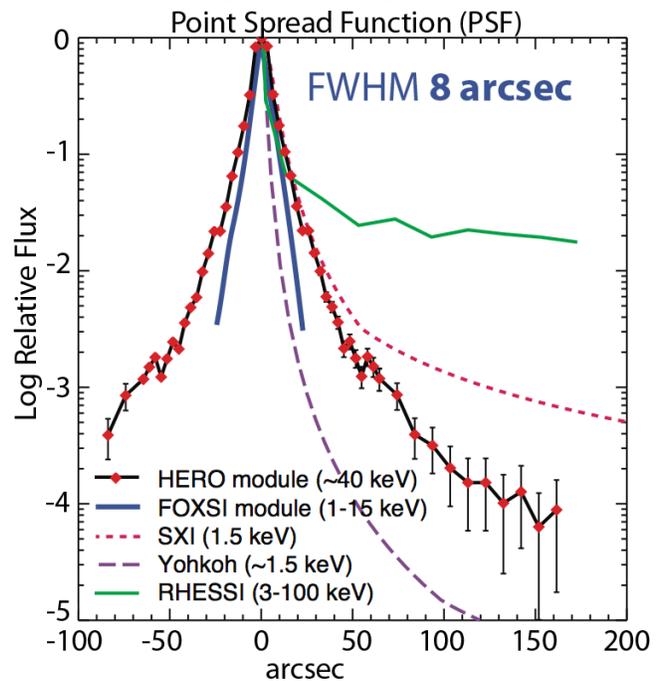
The Nuclear Spectroscopic Telescope Array (NuSTAR), scheduled for launch in 2012, is a NASA Small Explorer (SMEX) which uses glass HXR focusing optics for astrophysical observations in the 6 to 80 keV energy range (Harrison et al. 2010). NuSTAR consists of two co-aligned grazing incidence optics focusing on two shielded solid state CdZnTe pixel detectors 10 m away. It will provide observations of astrophysical objects with a sensitivity 50-100 times better than the past with an effective area of ~1000 cm^2. NuSTAR, though not optimized for solar observations (see Smith et al 2010 white paper), is an example of what a SMEX-like FOXSI mission with good spatial resolution could achieve.

The FOXSI sounding-rocket and NuSTAR are pathfinders for a future satellite-based FOXSI. Such a mission could be developed as a stand-alone mission in a SMEX-like budget similar to NuSTAR or could be part of a larger mission (e.g. RAM, SEE 2020, SSE white papers) with characteristics such a focal length appropriate to the mission. Table I describes one possible version of FOXSI with a 10 m focal length.

Conclusion

New technological advances in grazing incidence focusing optics and solid-state detectors now make it possible to observe the Sun in HXR with unparalleled sensitivity and dynamic range. **FOXSI will be able to image where electrons are accelerated along which field line they travel away from the acceleration site, where they are stopped, and how some electrons escape into interplanetary space while simultaneously providing detailed information about the energetics of these electrons as a function of time.**

Table I: FOXSI Strawman Mission/Instrument Characteristics. A larger mission can easily be scaled from this baseline concept mission.

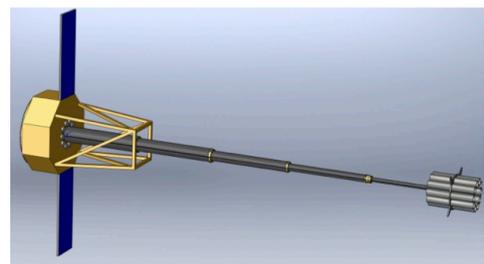|	
Focal length	10 m
Energy Range	1 to 60 keV
Energy Resolution	<1 keV
Spatial Resolution	8 arcsec (FWHM) corresponding to pixel size of ~400 μm
Field of View	~12 arcmin
Mass	100 kg (~3 cm^2/kg of optics)
Power	60 Watts
Dynamic Range	Up to 1000 (100 x RHESSI)
Sensitivity	100 x RHESSI
Cost (Mission)	SMEX
Cost (Instrument)	~$40M

Figure 5: FOXSI Strawman mission concept. For illustration, a FOXSI strawman concept with an expandable boom and seven telescope modules.

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