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Joint hard X-ray observations with ASO-S/HXI and SO/STIX

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Abstract This paper discusses the potential of future joint hard X-ray solar flare observations between the Hard X-ray Imager (HXI) onboard the Advanced Space-based Solar Observatory (ASO-S) mission and the Spectrometer/Telescope for Imaging X-rays (STIX) on Solar Orbiter. The different viewing perspectives of the two telescopes relative to the Sun will allow us for the first time to systematically study non-thermal hard X-ray emissions stereoscopically. During the 4-years of the nominal mission of ASO-S, we expect to jointly observe about 160 flares above GOES M1 class to systematically study hard X-ray directivity. For about 16 partially limb-occulted STIX flares, we will have observations of the entire flare by HXI. Such observations will enable us to simultaneously study the all-important coronal hard X-ray sources, which are generally lost in the instrument's individual imaging dynamic range, in combination with the chromospheric footpoint emissions. The two different detector systems used in the two telescopes make the relative calibration between the two instruments a key task that needs to be addressed before creditable science results can be published. If an accurate inter-calibration can be achieved using jointly observed flares on the disk, observations with HXI and STIX will provide new and essential key diagnostics for solar flare physics.

Key words: Sun: flares

1 INTRODUCTION

Hard X-ray observations are a key diagnostic for understanding the magnetic energy release processes and particle acceleration in solar flares. Through bremsstrahlung emissions, hard X-ray imaging spectral observations provide quantitative information on the hottest flare plasmas as well as accelerated electrons. Operation of the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI, Lin et al. 2002) during the past two solar cycles (2002 through 2018) has provided essential new input from the observational side. For reviews of the main RHESSI results, we refer to the RHESSI book (e.g., Lin 2011).

For the upcoming 25^{th} solar cycle, we are currently expecting two imaging spectroscopy observatories that apply a similar indirect imaging method as RHESSI to be operational: The Hard X-ray Imager (HXI) onboard the Advanced Space-based Solar Observatory (ASO-S) mission (Gan et al. 2015; Zhang et al. 2019) and the Spectrometer Telescope for Imaging X-rays (STIX, Krucker et al. 2019) onboard the Solar Orbiter mission. While ASO-S is an Earth orbiting satellite, Solar Orbiter will be on a trajectory around the Sun generally providing different viewing angles of the Sun as compared to Earth. Combined observations of these two telescopes will therefore provide, for the first time, systematic stereoscopic imaging spectroscopy observations of solar flares. In this paper, we explore the potential of such joint observations between HXI and STIX.

2 INSTRUMENT COMPARISON

The instrument parameters of HXI (in Phase-B) and STIX are listed in Table 1. Values of the angular scales and effective area for STIX are given for the nominal case, as well as adjusted for Solar Orbiter's closest approach (values given in brackets). For detailed instrument descriptions, we refer to Gan et al. (2019) and Zhang et al. (2019) for HXI and Krucker et al. (2019) for STIX.

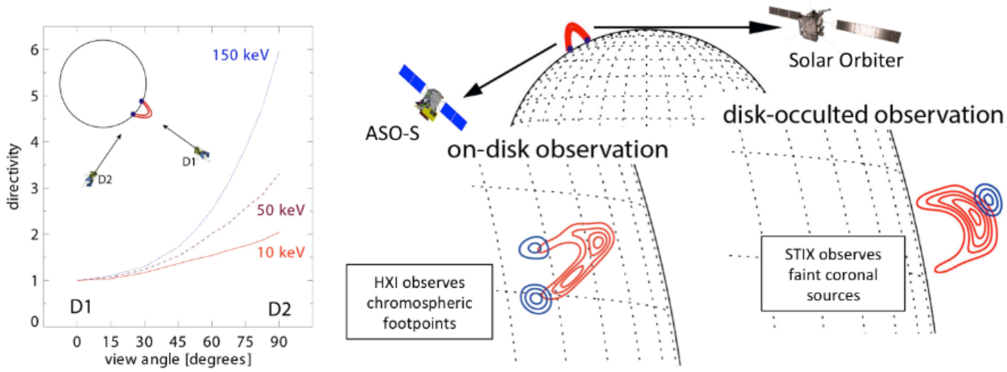

Fig. 1 Stereoscopic observations with HXI and STIX. *Left*: In the classic cold thick target model, electron beams penetrating the chromosphere are expected to produce anisotropic emissions. The plot shows the relative intensity of the hard X-ray footpoint emissions from different viewing angles with 0° and 90° corresponding to viewing angles from above (D1) and from the side (D2), respectively (after Brown 1971). *Right*: Limb-occultation allows us to make STIX observations with the bright chromospheric footpoints invisible making it possible to image much fainter coronal HXR sources that are otherwise lost in the limited imaging dynamic range of the indirect imaging systems. HXI will provide the otherwise missing observations of chromospheric footpoints to facilitate modeling the time evolution of the entire event.

The performances in sensitivity and angular resolution of the two instruments are similar when considering that STIX will acquire observations from a closer distance to the Sun. One of the differences in the two instruments is that HXI is operating in a single photon counting mode, but STIX is forced to bin individual counts onboard in both time and energy in order to stay within the allocated telemetry. The main difference is the energy range and spectral resolution. STIX will sample both the thermal and non-thermal range of the solar flare spectrum with an energy resolution around 1 keV, while HXI observes only the non-thermal spectrum extending to higher energies, but at lower spectral resolution. This second difference has a significant impact on joint observations. It limits the observations to only large flares, such as flares above M class. Furthermore, the difference in spectral resolution makes a spectral comparison a more challenging task and puts a strong emphasis on the detector calibration.

3 OBSERVATIONS

In this section, we first derive the expected number of jointly observed flares followed by the discussion of joint observations of on-disk and occulted flare studies.

3.1 Number of Expected Events

In the following, we estimate the number of large flares, here defined as larger than GOES M1 class, that we expect to detect during HXI's 4-year nominal mission. From the previous solar cycles, we estimate that there will be ∼80 M-class flares per year during solar maxima. Hence, we expect a total of 320 M-class flares will be recorded during the nominal phase of ASO-S, assuming a 100% duty cycle. Half of these events should also be seen by STIX assuming uninterrupted STIX observations. The current plan for STIX is indeed to be operational at all times in synoptic mode, and therefore we expect about 160 jointly observed M-class flares over 4 years. Inside Solar Orbiter science windows (30 days out of the 180 day orbit) where enhanced telemetry is allocated to all remote sensing instruments, the number of jointly observed flares reduces to about 50 events in 4 years.

Occulted flares are best observed if they occur between a few and 15 degrees behind the limb. For simplicity, we assume here that the range is ∼10 degrees. This value depends on the actual flare geometry and should therefore be understood as an estimate derived from RHESSI observations (e.g., Krucker & Lin 2008; Effenberger et al. 2017). Considering that on-disk flares span over 180 degrees and occultation can happen at either limb, the value of ∼10 degrees indicates that the number of occulted flares is of the order of about 10% of all detected flares. Hence, of the 320 M-class cases detectable during the nominal phase, we expect to have about 32 occulted flares in the HXI database, and half of them will be seen by STIX, assuming again a 100% duty cycle. Additionally, we will have the same number of occulted STIX flares for which HXI will see the flare on the disk. Similarly, we can estimate that we will detect about 16 flares for which HXI and STIX will be able to see the flare from the same viewing direction within 10 degrees of each other, a circumstance that is useful for cross calibration.

Published RHESSI statistical studies of occulted flares can be used to check if the numbers derived above are realistic. For the last solar maximum, Effenberger et al. (2017) reported an average of 4.5 occulted RHESSI flares per

Table 1 Instrument Performance Comparison between HXI and STIX

Parameter	HXI	STIX
Energy range	30–200 keV	4–150 keV
Spectral resolution at 40 keV	$\sim$8 keV	$\sim$1 keV
Spectral binning	photon counting	32 bins (adjustable)
Sampled angular scales	$3''$ to $125''$	$7''$ to $224''$ ($2''$ to $63''$)
Field of view	full Sun	full Sun
Effective area	$180\,\mathrm{cm}^2$	$6\,\mathrm{cm}^2$ ($70\,\mathrm{cm}^2$)
Sampling time	>0.125 s	>0.1 s
Calibration scheme	onboard source	onboard source
Estimated background at 40 keV	$\sim 20\,\mathrm{ph\,s^{-1}\,keV^{-1}}$	$\sim 30\,\mathrm{ph\,s^{-1}\,keV^{-1}}$

year above GOES M class. After correcting for RHESSI's duty cycle, this corresponds to 7.5 flares per year, or 30 flares over 4 years. These numbers correspond well with the 32 flares estimated above. We note here that the study of Effenberger et al. (2017) also included occulted flares smaller than M class, and the total number of flares reported in Effenberger et al. (2017) is about four times higher than estimated just for M-class flares. This indicates that the number of 16 jointly detected HXI-STIX flares mentioned above is possibly a conservative limit.

The number of events detected for larger flares can be estimated using the observed frequency distribution of GOES peak fluxes from Veronig et al. (2002). The frequency distribution is reported to have a slope of roughly 2. Hence, the number of flares above a given class scales with flux. For flares above M2, M5 and X1, the number of events is therefore roughly reduced by a factor of 2, 5 and 10, respectively.

3.2 On-disk Flares for Both Observatories

Jointly observed on-disk flares will be utilized to investigate the directivity of the non-thermal hard X-ray signals from the chromospheric footpoints of solar flares. In the classic cold thick target model (Brown 1971), the emissions from footpoints are expected to be clearly beamed (see Fig. 1, right). However, such anisotropic emissions have not been observed. On the contrary, Kontar & Brown (2006) demonstrated that RHESSI single perspective observations are consistent with an isotropic emission pattern, when considering that the observed emission is composed of a direct signal and an albedo component. However, to date there are no systematic stereoscopic observations that confirm these indirectly derived results. Joint observations with HXI and STIX will for the first time provide such a statistical sample that directly measures emission patterns from flaring footpoints. However, the different spectral resolutions of the two instruments will complicate such measurements. To be able to make directivity measurements will put stringent requirements on the accuracy of the calibration. The few jointly observed flares (see Sect. 3.1) with similar viewing angles can be applied to confirm the calibration.

We note here that, besides the science objective, joint imaging observations of flares on the disk can furthermore be used for the following three topics: (1) Confirm the cross calibration of the energy response of the two instruments; (2) Confirm the absolute pointing offset and the absolute roll aspect of each instrument is within specifications; and (3) Enhanced imaging by combining calibrated visibilities from each instrument to improve uv coverage.

3.3 Occulted Flares

As the density in the chromosphere is much higher than in the corona, non-thermal bremsstrahlung is dominated by emissions from the chromosphere. With the limited dynamic range of indirect imaging systems such as HXI and STIX (typically, 30% contours indicate reliable sources, with a few events that manifest sources at the level of 10% of the peak emission), only emissions from the chromosphere are generally imaged. Fainter emissions are lost in the noise produced by the imaging reconstruction process. The lack of observations from coronal hard X-ray sources is currently the main observational shortcoming of hard X-ray flare physics (e.g., Krucker et al. 2010). To compile information on the all-important coronal emissions that originate closest from the acceleration site, solar limb-occultation has been employed (e.g., Krucker & Lin 2008). Such observations clearly reveal the existence of coronal non-thermal bremsstrahlung emissions, but for those events, the main chromospheric flare emissions are not observed, preventing modeling of the flare evolution. With the stereoscopic observations supplied by HXI and STIX, we will, for the first time, be able to systematically study the chromospheric footpoints and coronal sources at the same time. As the coronal sources are fainter and generally show a softer spectrum, occulted sources are best seen around and below 30 keV, but occasionally extend up to 100 keV (e.g., Krucker et al. 2010). HXI will therefore be less effective in detecting occulted flares compared to STIX, in particular considering that the lower energy HXI counts around 30 keV might still include contributions from the thermal counts due to the 20% spectral resolution. The best sample of events will therefore be for flares that are occulted from the Solar Orbiter view, while HXI provides the chromospheric observations. Nevertheless, some of the events occulted from the Earth view will provide valuable data as well, as long as the coronal emissions extend well into the HXI energy range. The disadvantage for occulted flares seen by STIX is that no imaging of the total thermal HXR imaging will be available. Occulted events as seen from STIX, on the other hand, will have the advantage that context observations from the Earth view are generally much more readily available.

3.4 Additional Hard X-ray Observations

The joint HXI/STIX observations would benefit from additional hard X-ray observations, even if only spectral information is obtained without imaging. A prime candidate is the HEL1OS hard X-ray spectrometer onboard India's Aditya mission which will be operating from L1 starting in 2021. With additional spectral observations, the calibration can be double checked, and additional information on spectra below the HXI energy can be obtained. Other candidates for spectral observations are cubesat missions, such as MinXSS (Moore et al. 2018) or IMPRESS.

4 SUMMARY

Joint observations between HXI and STIX represent great potential for two key areas of solar flare research: The study flare-accelerated electron distribution through the observation of hard X-ray directivity in chromospheric footpoints and the evolution of coronal sources relative to chromospheric footpoints. Both of these topics are essential key diagnostics to understand solar flare physics, but could not be properly addressed with past observations. While the number of simultaneous events will be large enough for statistical work, the main concern is the required accuracy of the relative calibration between the two instruments. The HXI spectral resolution of about 20% at 50 keV complicates the spectral comparison. Careful calibration strategies need to be developed in the near future, and scientific results can only be published after the inter-calibration accuracy can be quantified.

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