

High-sensitivity hard X-ray solar observation with the FOXSI rocket



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Introduction

- Hard X-ray (HXR, $>$ a few keV) provides important information about the energy release process in the Sun

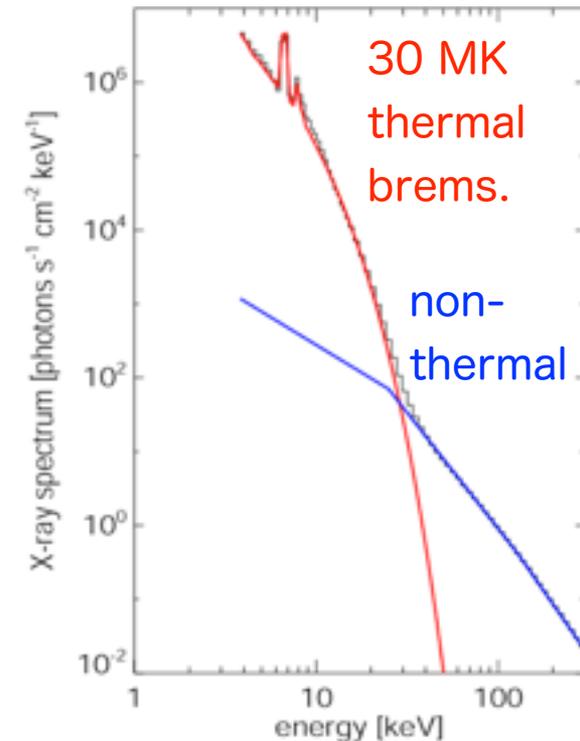
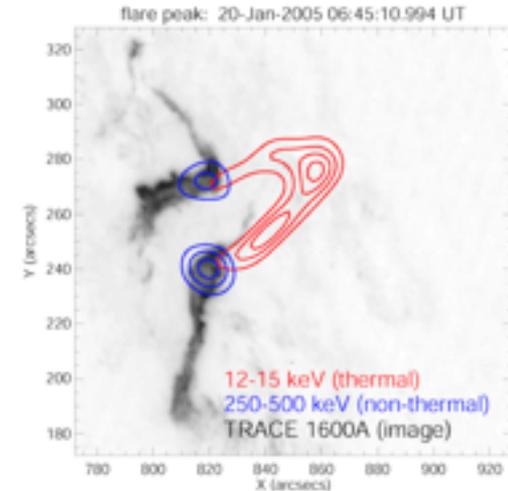
Thermal emission :

- Thermal bremsstrahlung from hot plasma ($>$ a few MK) associated with flares i.e. post flare loops

Non-thermal emission :

- Non-thermal bremsstrahlung emission from accelerated particles
- Dominant at higher energies

HXR imaging and spectroscopy is important tool to investigate high-energy process, good combination with coronal observation by Hinode/XRT and EIS



Sensitivity limitations

- More HXR observations (imaging and spectroscopy) are desired, especially for:

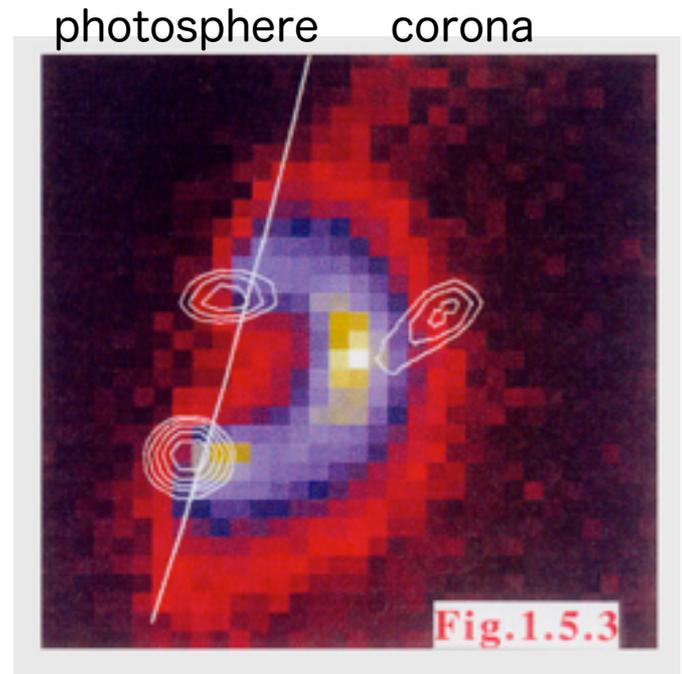
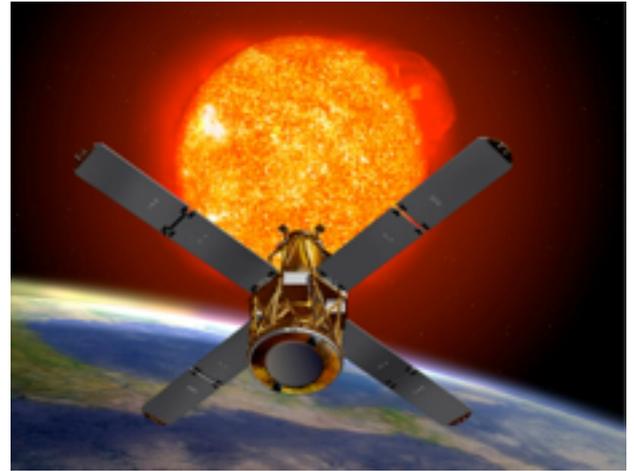
(1) Hot thermal component of non-flaring active regions

- (2) Non-thermal emission from the quiet Sun
- (3) Emissions from coronal sources in flares

- Yohkoh/HXT and RHESSI use the modulation collimators (image reconstruction is needed)
 - Sensitivity and dynamic range are limited
 - All position determined RHESSI HXR events are from active regions
 - (Christe et al. 2008; Hannah et al. 2008)

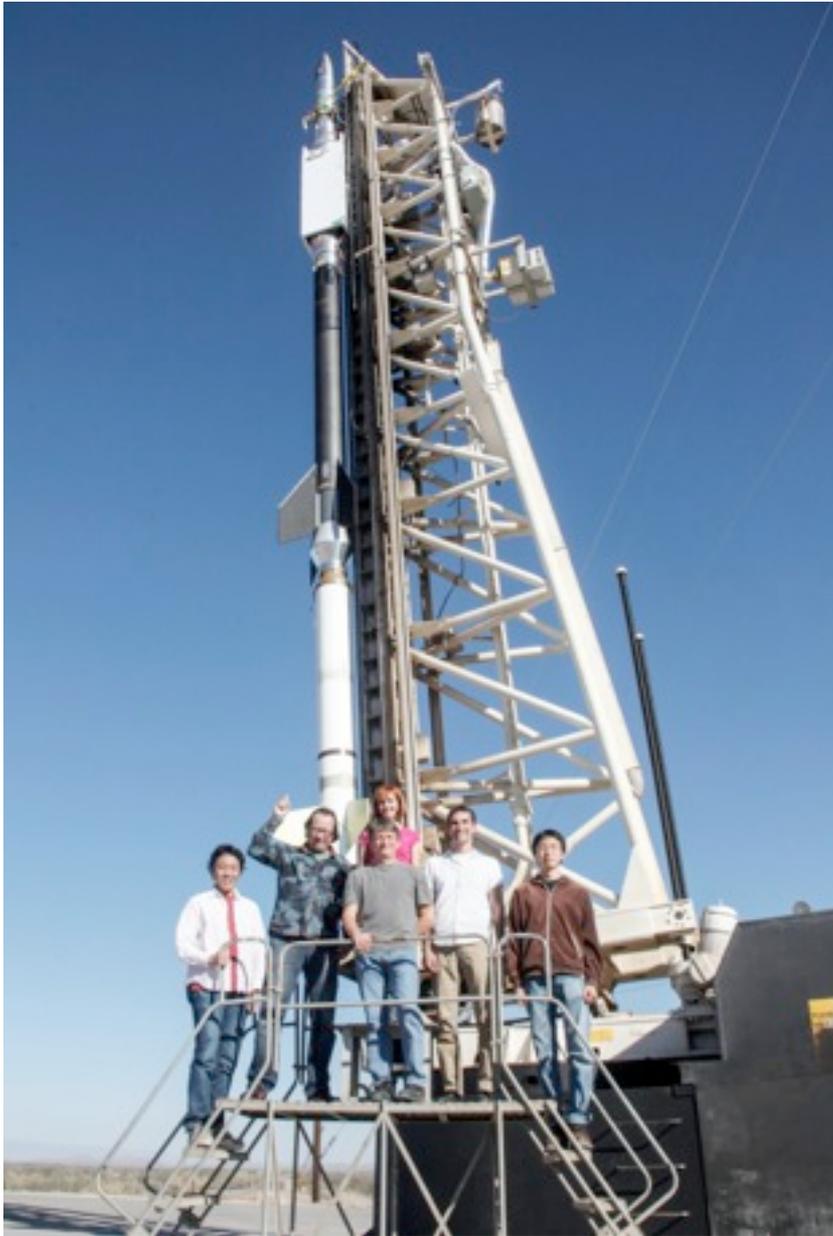
- New technique for HXR imaging and spectroscopy is necessary:

-> Recently HXR focusing optics are put into practical use, and we tested them with a sounding rocket: FOXSI



(Masuda et al., 1994)

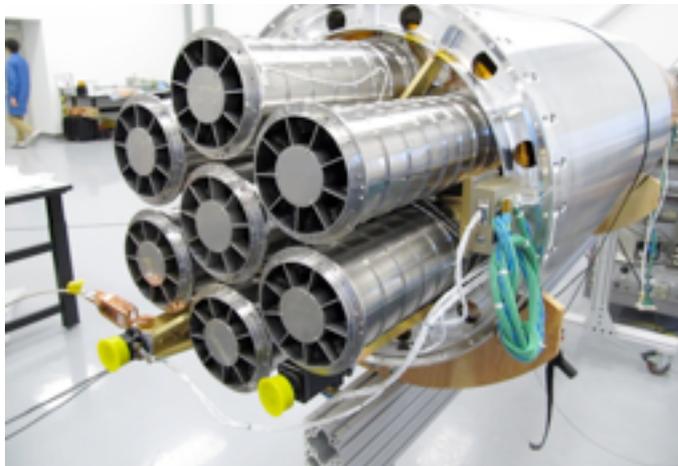
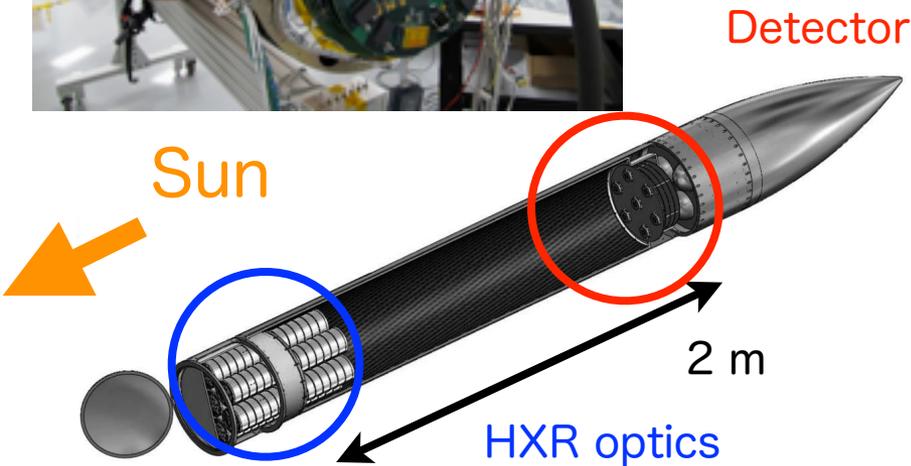
The Focusing Optics X-ray Solar Imager (FOXSI)



- International rocket mission for high sensitivity HXR imaging and spectroscopy using HXR optics and realtime photon-counting detector
SSL/UCB, NASA/MSFC and ISAS/JAXA

- Major motivations:
 - High-temperature component of non-flaring active regions
 - Is there any non-thermal emission from the quiet Sun?
 - Technology validation and demonstration of HXR imaging and spectroscopy of the Sun using HXR optics

FOXSI instrument

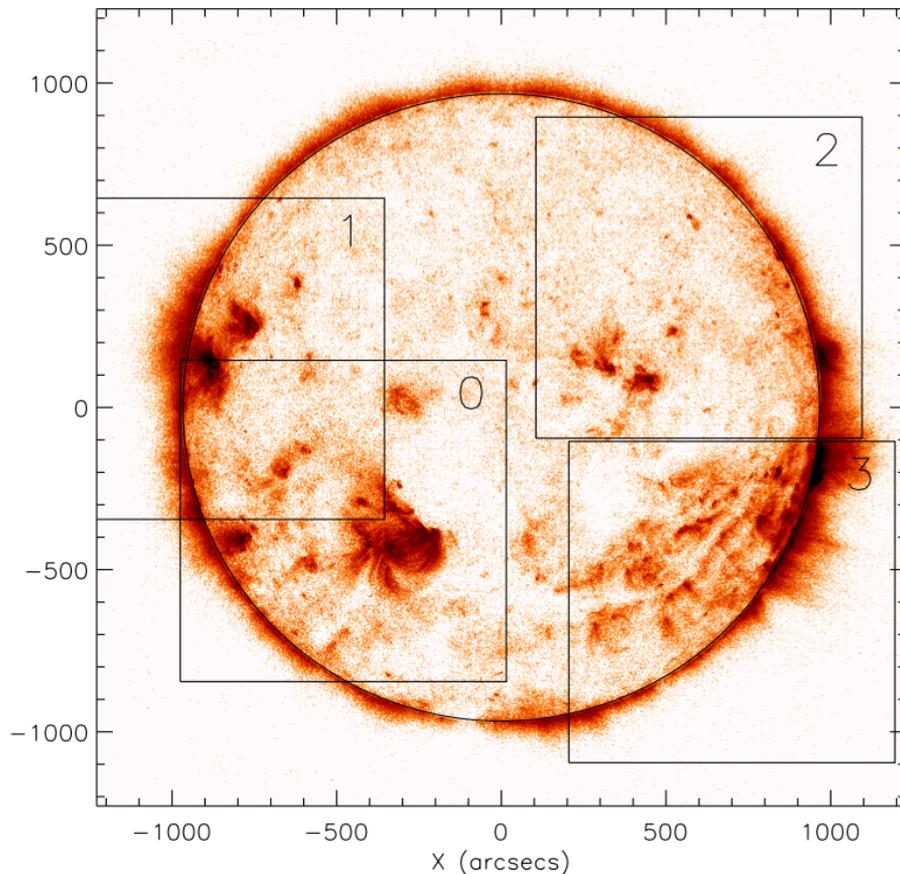


- Focusing and imaging achieves smaller detector volume with higher effective area than RHESSI
-> lower background, higher sensitivity
- 7 pairs of HXR optics and focal plane detectors (same configuration)
- Observation time ~5 min, Energy range 5-15 keV (Energy resolution: 0.5 keV FWHM) Position resolution ~6''
- >10 times better sensitivity and dynamic range (8 keV) than RHESSI
- Successfully launched at Nov. 2, 2012 at White Sands Missile Range (New Mexico, USA)

FOXSI and Hinode observations - pointings

We believed we can easily find >5 keV emission in active regions, so we planned to check that instruments are working fine by pointing active region first

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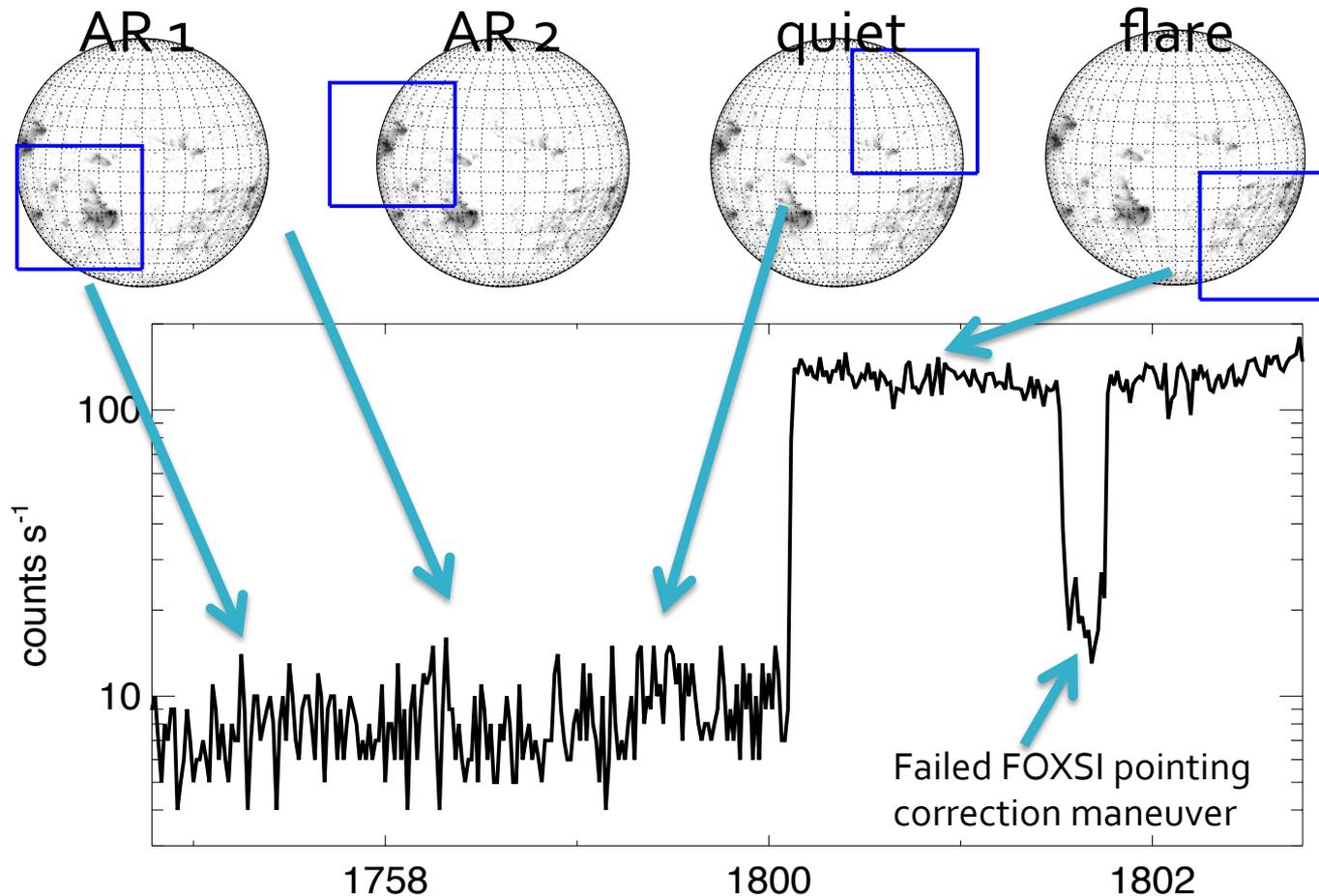
FOXSI pointing plan:

- 0: Active region 1
- 1: Active region 2
- 2: Quiet Sun
- 3: backup target (AR)

Hinode observation (HOP 221):

- Before/after the FOXSI launch window
 - Active region DEM (EIS, XRT)
- During the launch window:
 - Quiescent region high cadence

FOXSI observation



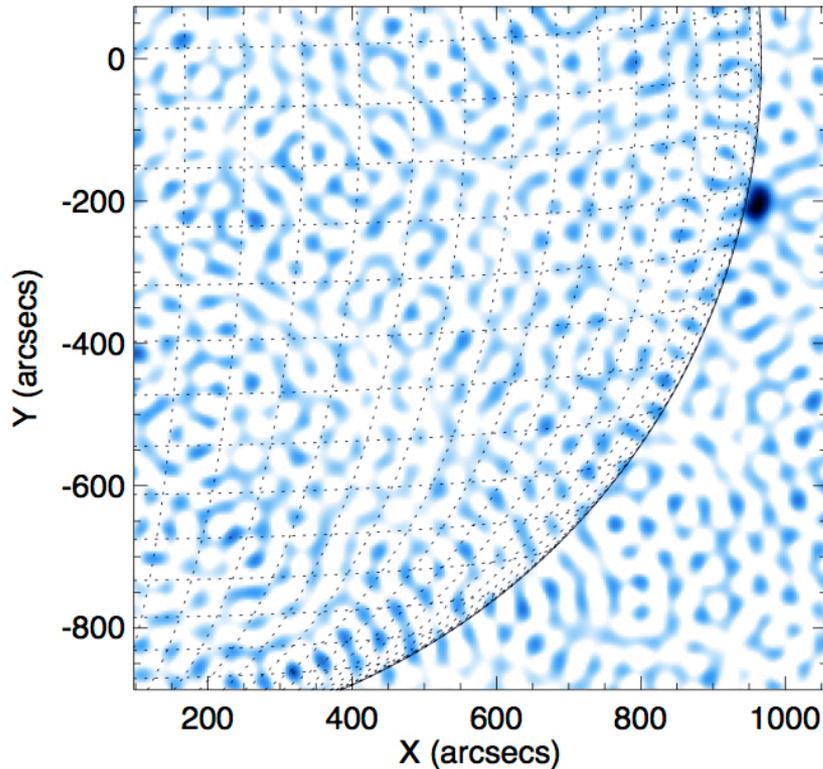
hhmm
2012 Nov 02

- Strong emissions are not detected from first 3 target (2 ARs, QS)
Significant counts are detected by the flaring active region (backup target)
- The detected event was found to be a flare (GOES class B4)
it was very fortunate that HXR flare occurred in 5 minutes!!

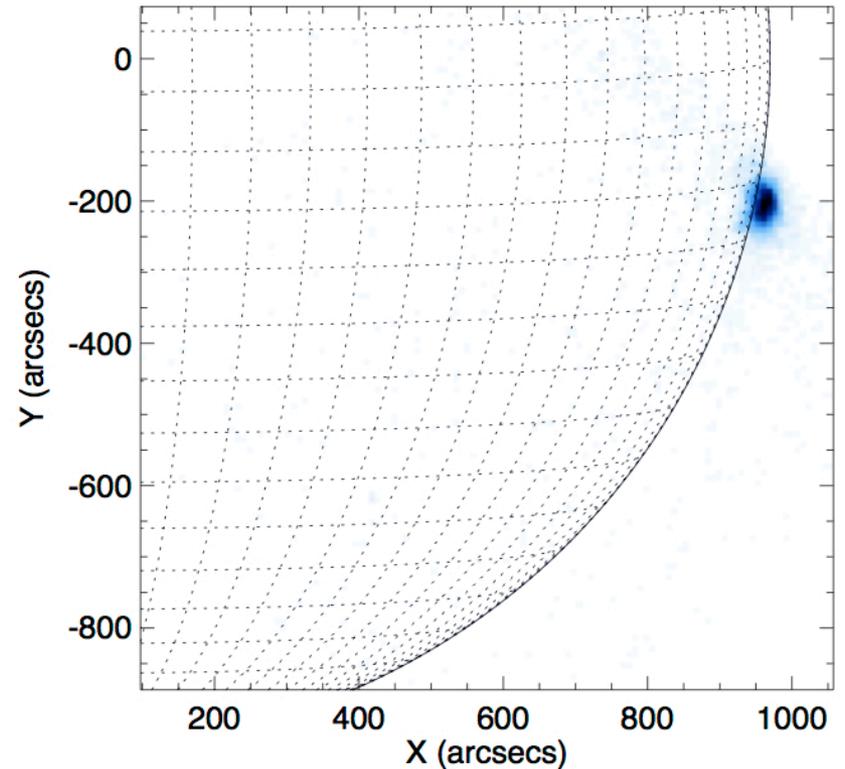
Images of the flare

- RHESSI also detected this flare -> cross calibration can be done

RHESSI



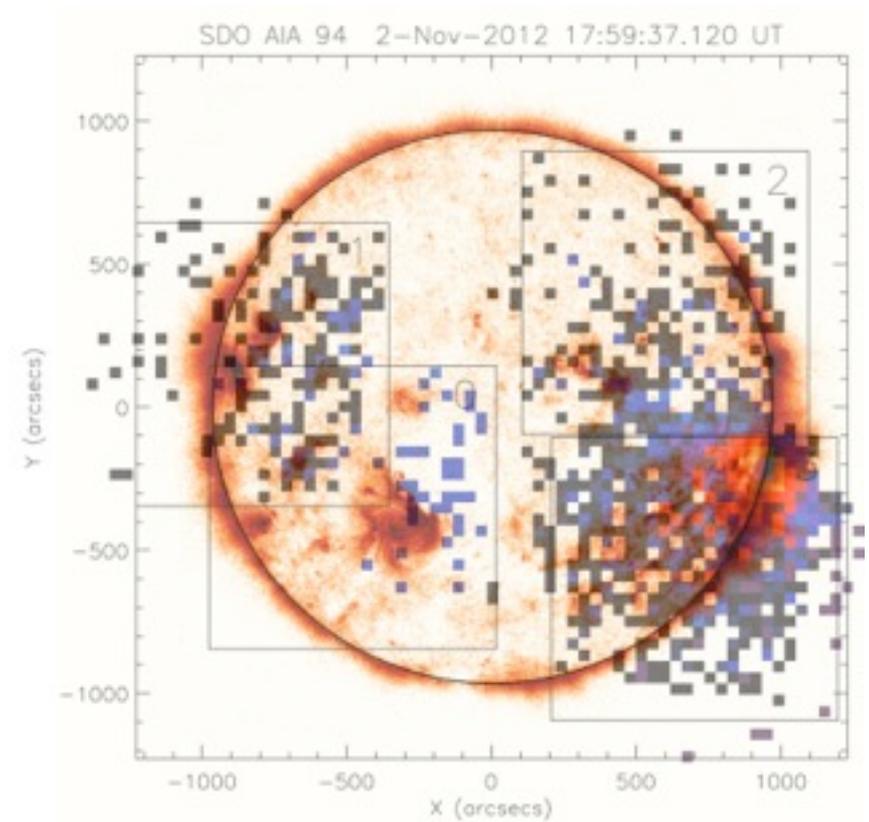
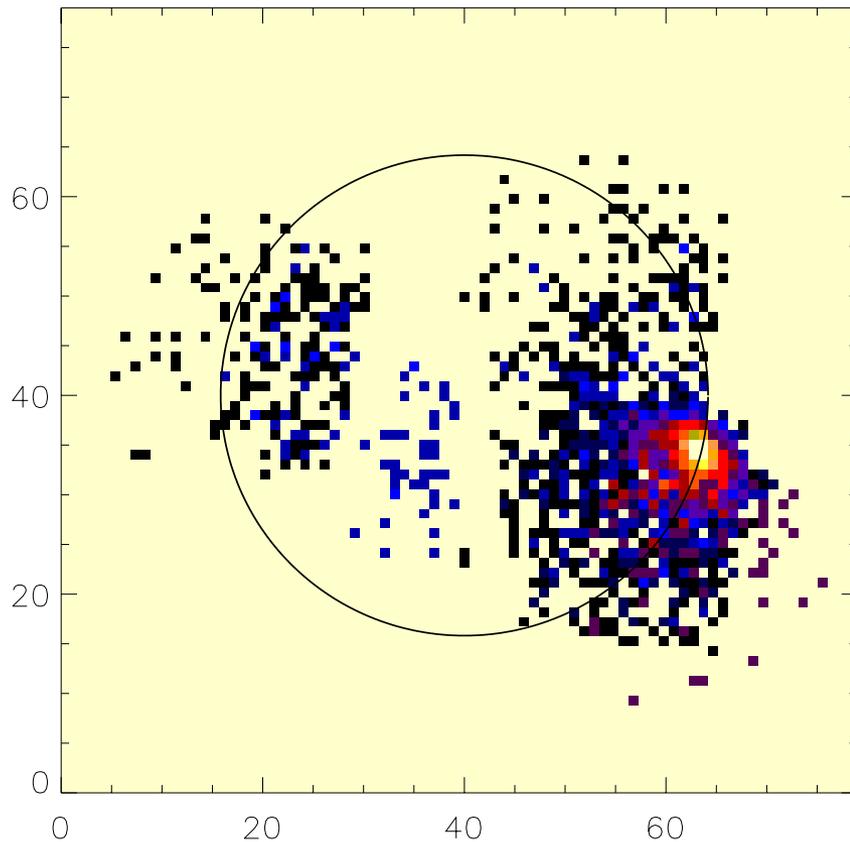
FOXSI



- Although RHESSI has a very complex PSF because Fourier image reconstruction is necessary to obtain image (indirect imaging), FOXSI has a very clear PSF
- It is clearly confirmed that the FOXSI instrument works fine, and Very high sensitivity is clearly demonstrated!

Image of all the counts

- 4-15 keV, excluding bad data packet, log scale
- Although it looks X-rays are detected also in non-flaring region, no significant difference cannot be seen between non-flaring ARs and quiet Sun -> [upper limit of AR emissions](#)

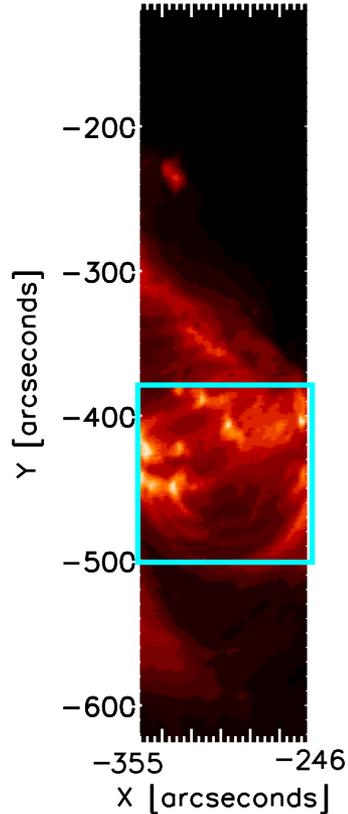


Hinode Observation of AR

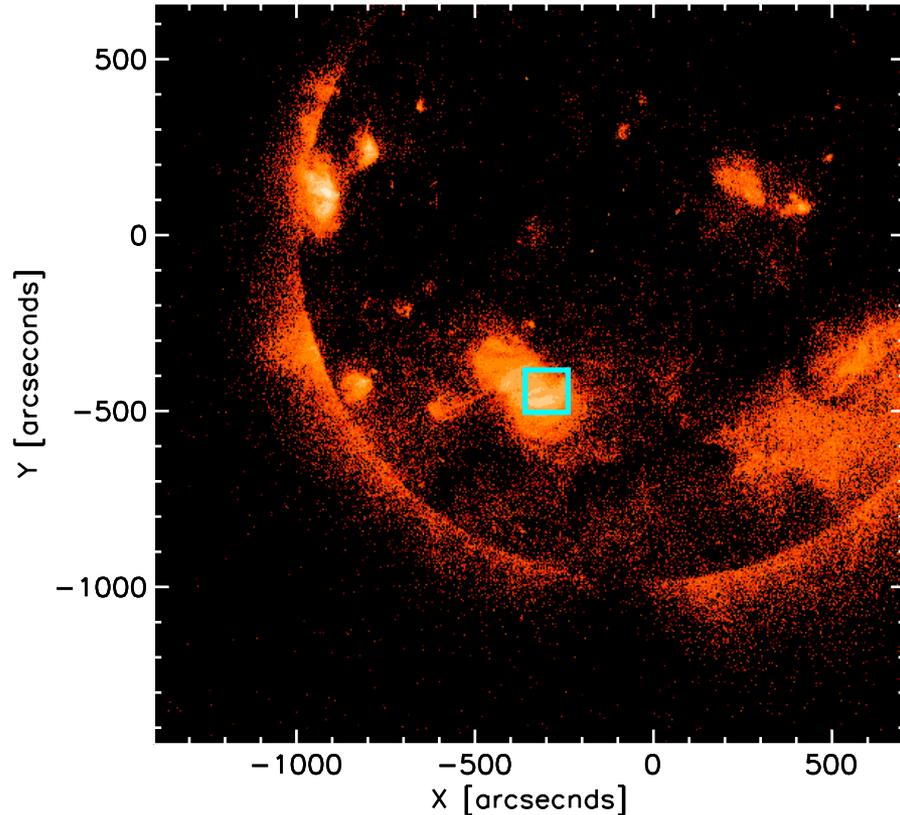
EIS: 1'' slit scan, 25 band

XRT: Multi-filter observation (11 filter pairs)

EIS Fe XII 195.12 nm



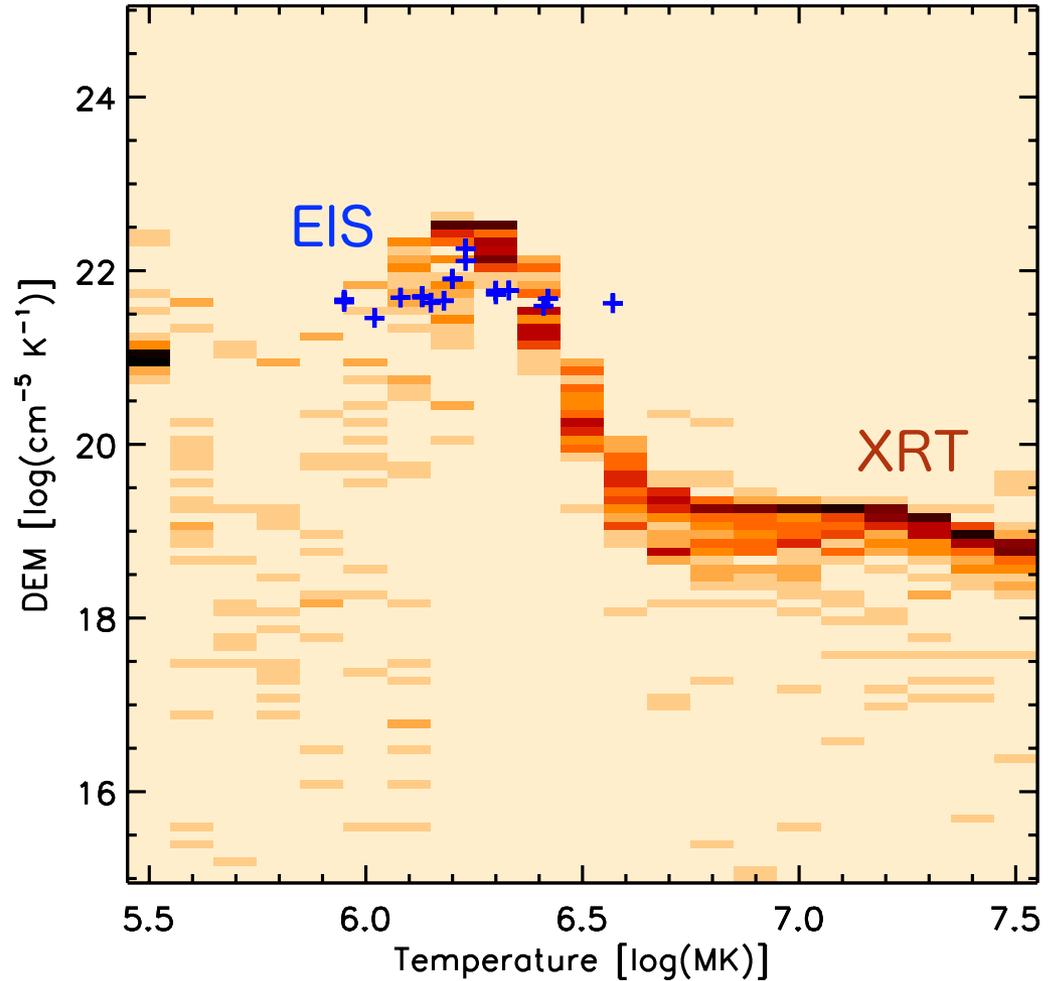
XRT Al-poly (logscale)



- We estimated the differential emission measure of the first target AR of FOXSI
- XRT multifilter analysis with 100 Monte Carlo (`dem_xrt_iterative2.pro` in SSW)
 - EIS line spectroscopy (`chianti_dem.pro` in SSW)

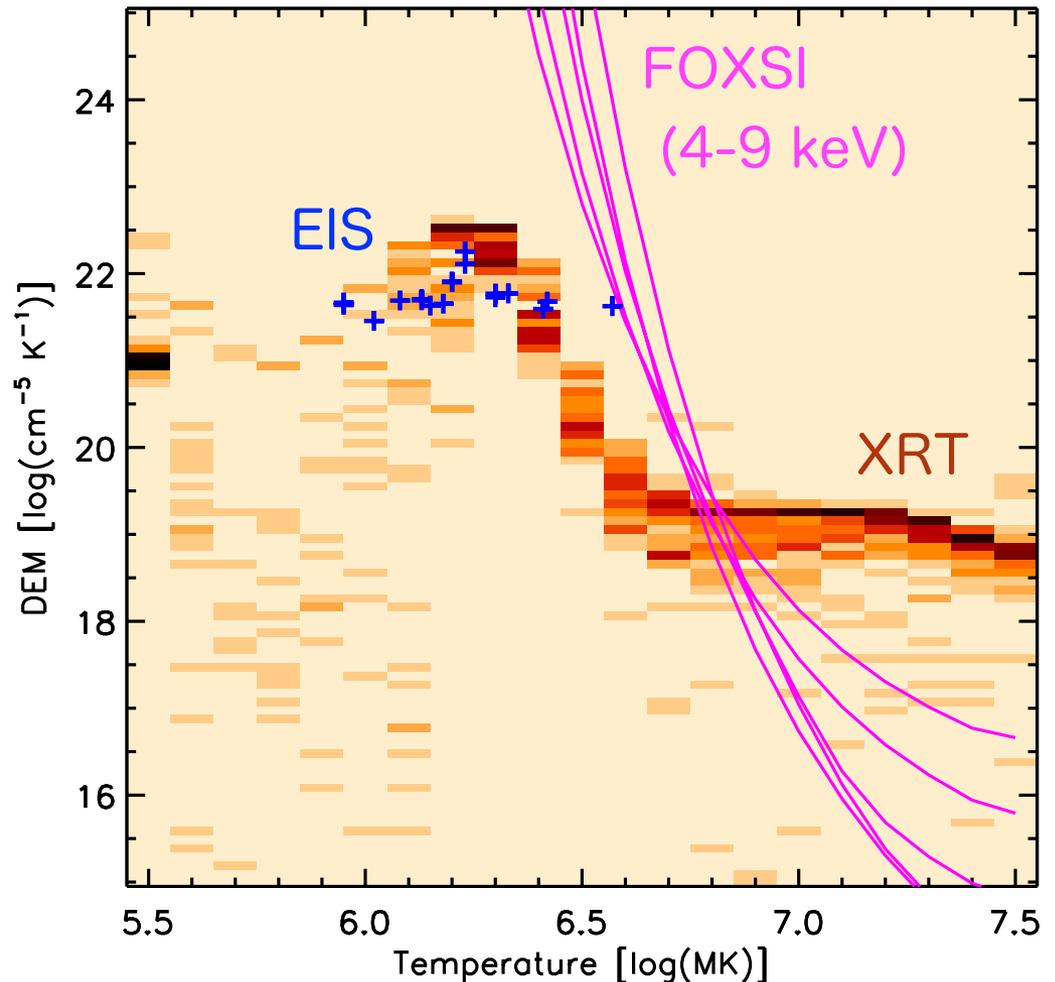
Differential Emission Measure

- XRT DEM peaks at $\log T \sim 6.2-6.3$, and hot component can be seen by the XRT analysis even with $\log T > 7.0$



Differential Emission Measure

- XRT DEM peaks at $\log T \sim 6.2-6.3$, and hot component can be seen by the XRT analysis even with $\log T > 7.0$
 - We compared with FOXSI data
Loci curve for each 1 keV energy bin is shown
 - FOXSI loci curves show, if the XRT DEM is correct, much more emissions should be detected by FOXSI
- > This suggests the absence of hot ($\log T > 6.8$) component in this AR



Summary

- Focusing optics HXR imaging and spectroscopy is strong tool to investigate faint HXR sources, such as non-flaring active regions
- We launched the FOXSI rocket on Nov. 2, 2012, and successfully demonstrated high sensitivity and dynamic range HXR observation of the Sun
- We compared FOXSI active region observation with Hinode observation and we cannot find hot plasma ($\log T > 7.0$) predicted by the XRT DEM analysis

Future Plan:

- The second launch is scheduled (FOXSI-2, to be launched in 2014)
We update the instrument to obtain higher effective area
- We plan to propose a satellite using FOXSI type instrument for further study