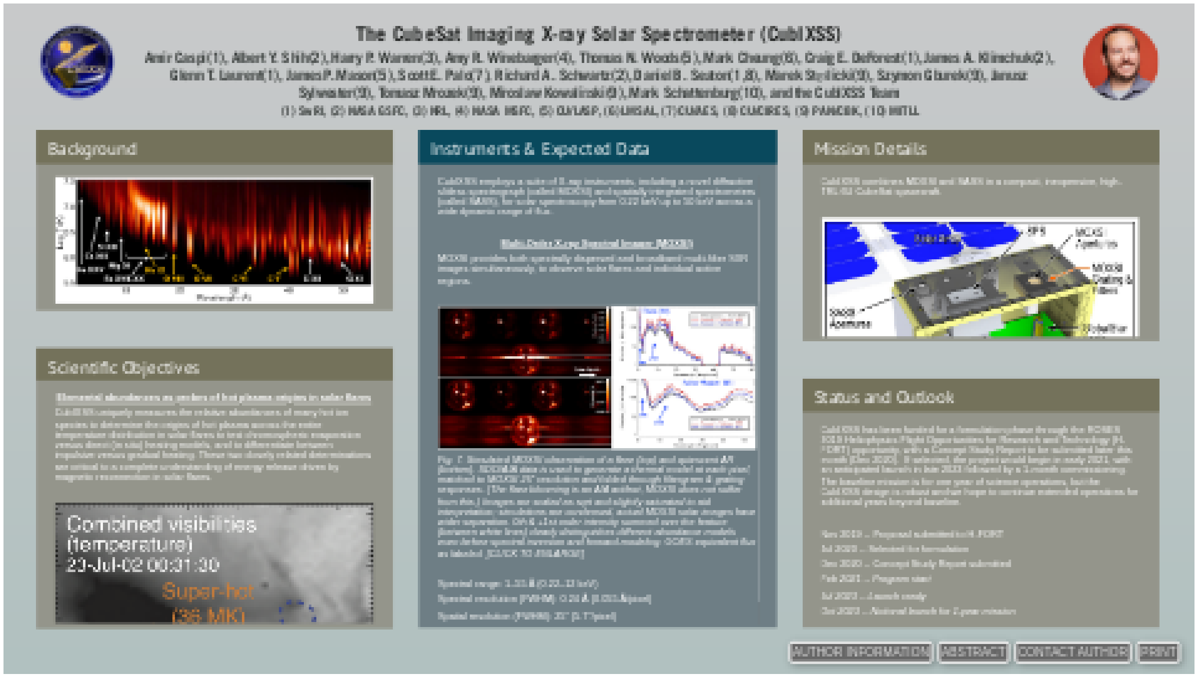
The CubeSat Imaging X-ray Solar Spectrometer (CubIXSS)



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PRESENTED AT:

BACKGROUND

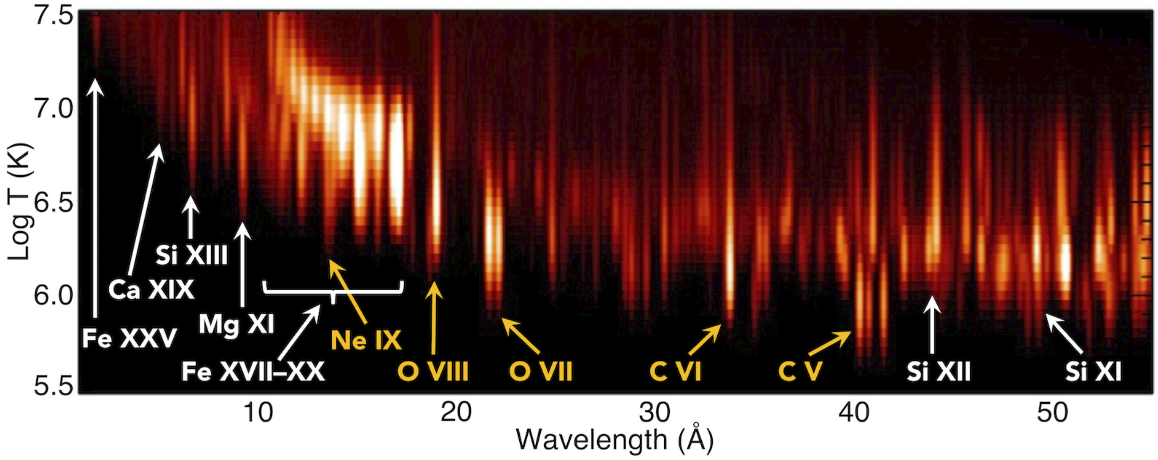


Fig. 1. CubIXSS will measure emission from hot ions across the full range of coronal plasma temperatures, from ~1 to >30 MK. CHIANTI calculations of plasma emissivity vs. wavelength and temperature show many bright, hot emission lines for both low- (white text) and high-FIP (https://en.wikipedia.org/wiki/Ionization_energy) (orange text) ion species. [CLICK TO ENLARGE]

How the corona is heated to tens of megakelvin (MK) in solar flares and quiescent (non-flaring) active regions is still poorly understood. Elemental abundances are a unique diagnostic of how mass and energy flow into and within the corona. Spectral signatures of key trace ion species reveal the chromospheric or coronal origins of hot plasma, constraining heating locations and mechanisms. However, many prior studies of abundances have yielded conflicting results, largely because they relied on instruments with limited, differing temperature and composition sensitivities.

Soft X-ray (SXR; 0.1–10 keV or 1–100 Å) emission provides unique diagnostics, unavailable in EUV, for high-temperature plasmas. This wavelength range includes both continuum emission and, crucially, numerous spectral lines (Fig. 1) that sample elemental composition across the full range of temperatures in solar flares and active regions. SXR observations with good spectral resolution across a broad passband thus measure the abundances of many hot ions, with both low and high first ionization potential (FIP) (https://en.wikipedia.org/wiki/Ionization_energy), to probe plasma heating processes.

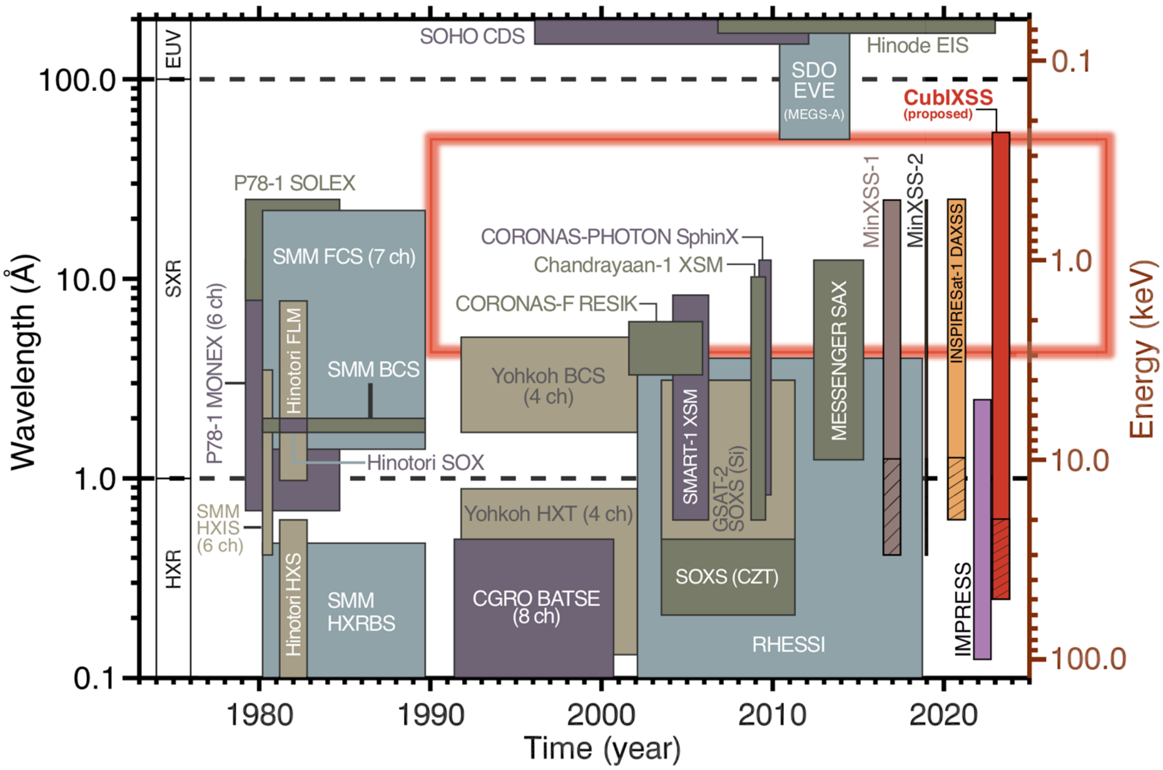


Fig. 2. CubIXSS bridges a critical gap in SXR solar spectroscopy. The 0.25–3 keV (4–50 Å) region, highlighted, has never been completely covered and has been studied only sporadically in recent years. CubIXSS (red, right) will fill this crucial gap to enable detailed abundance measurements. [CLICK TO ENLARGE]

However, spectrally resolved SXR solar observations have been rare, with only sporadic (and incomplete) coverage of the crucial 0.25–3 keV (4–50 Å) wavelength range for more than 30 years (Fig. 2). CubIXSS SXR observations fill this key measurement gap, for the first time, to determine the plasma composition across a wide temperature range and enable new insights into the decades-old question of where and how coronal plasma is heated.

SCIENTIFIC OBJECTIVES

Elemental abundances as probes of hot plasma origins in solar flares

CubIXSS uniquely measures the relative abundances of many hot ion species to determine the origins of hot plasma across the entire temperature distribution in solar flares to test chromospheric evaporation versus direct (in situ) heating models, and to differentiate between impulsive versus gradual heating. These two closely related determinations are critical to a complete understanding of energy release driven by magnetic reconnection in solar flares.

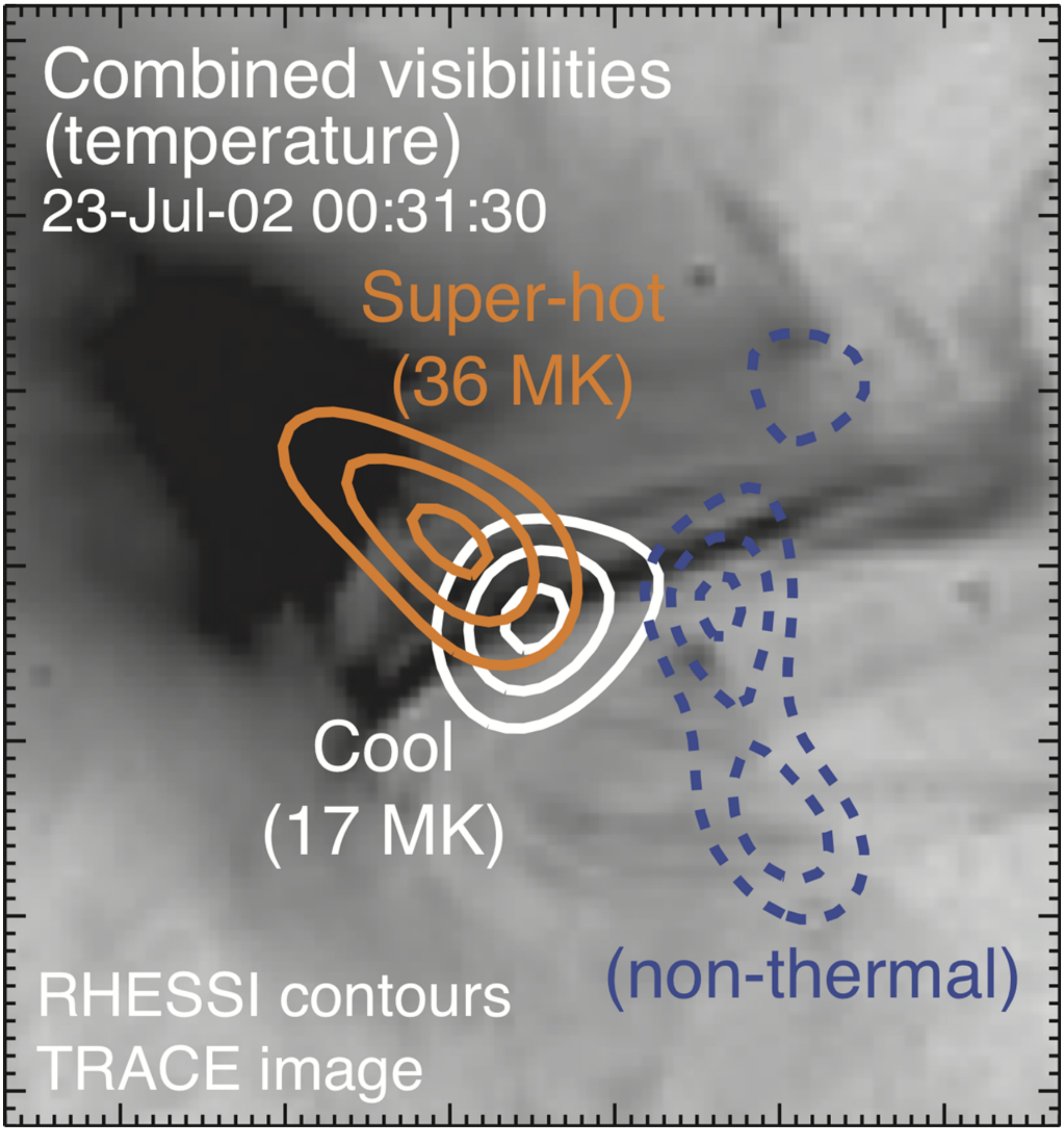


Fig. 3. HXR imaging spectroscopy with EUV context (adapted from Caspi et al. 2015a (https://doi.org/10.1088/2041-8205/811/1/L1)) suggests, circumstantially, that much of the thermal plasma, particularly at high T, is directly heated in the corona. CubIXSS resolves the origins of hot plasma across the entire flare temperature distribution through spectroscopic SXR measurements of elemental abundances (see Fig. 4, below). [CLICK TO ENLARGE]

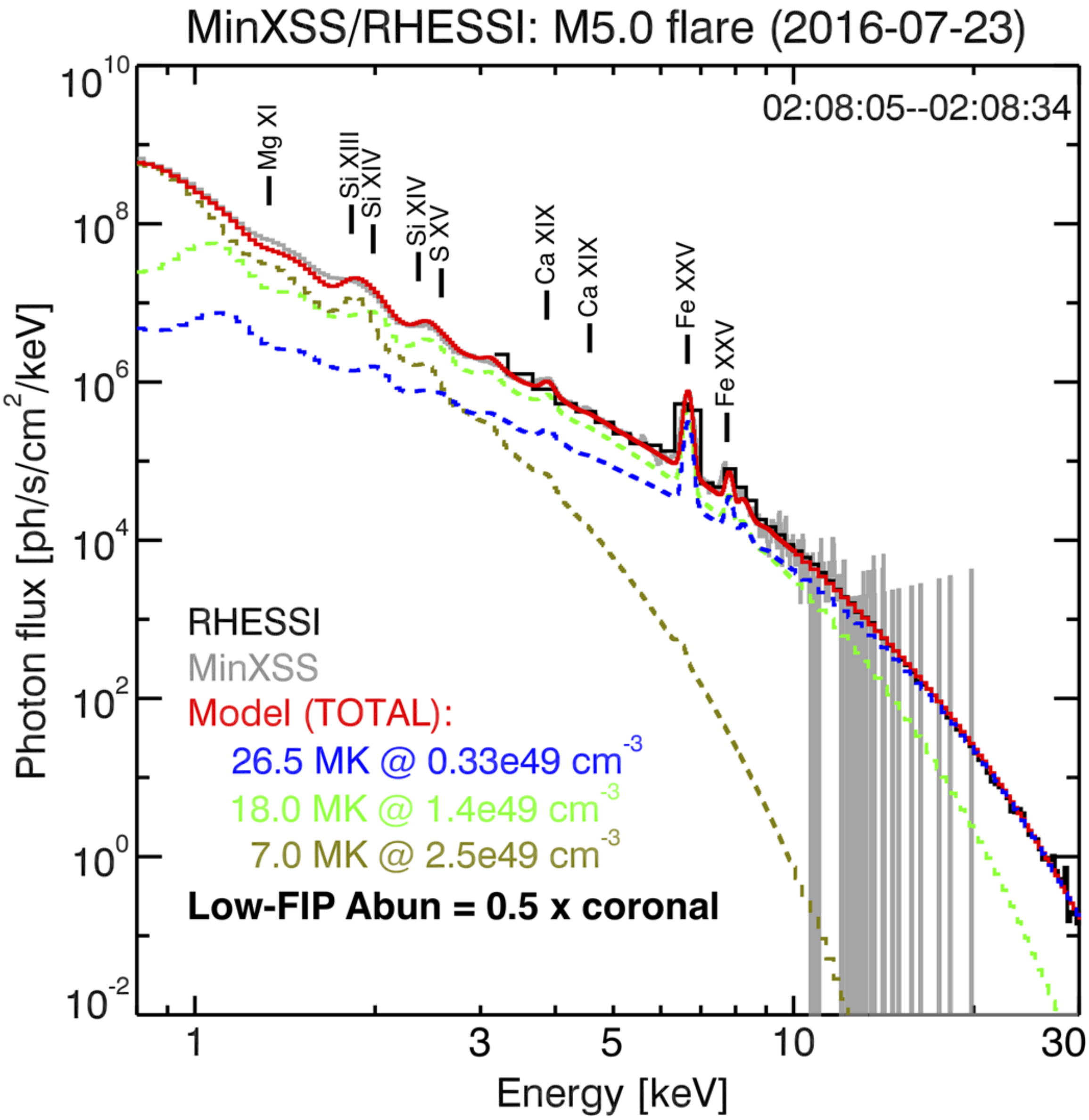


Fig. 4. MinXSS+RHESSI spectra for an M5 flare suggests a low-FIP bias of ~2 (applied uniformly to all indicated ions). CubIXSS combined MOXSI+SASS spectra enable self-consistent abundance determinations for more elements, individually, across the entire flare temperature range of ~1 to ≳30 MK. [CLICK TO ENLARGE]

Developing new capabilities for measuring abundances in active regions

CubIXSS demonstrates important technology for future X-ray spectrospatial imagers. While single-pixel spectrometry is useful for large flares, spatial resolution is important to distinguish the spectra of individual active regions or simultaneous flares. CubIXSS demonstrates multiorder slitless spectral imaging deconvolution/separation techniques in the context of SXR spectra of active regions, enabling studies from future instruments to exploit this technology.

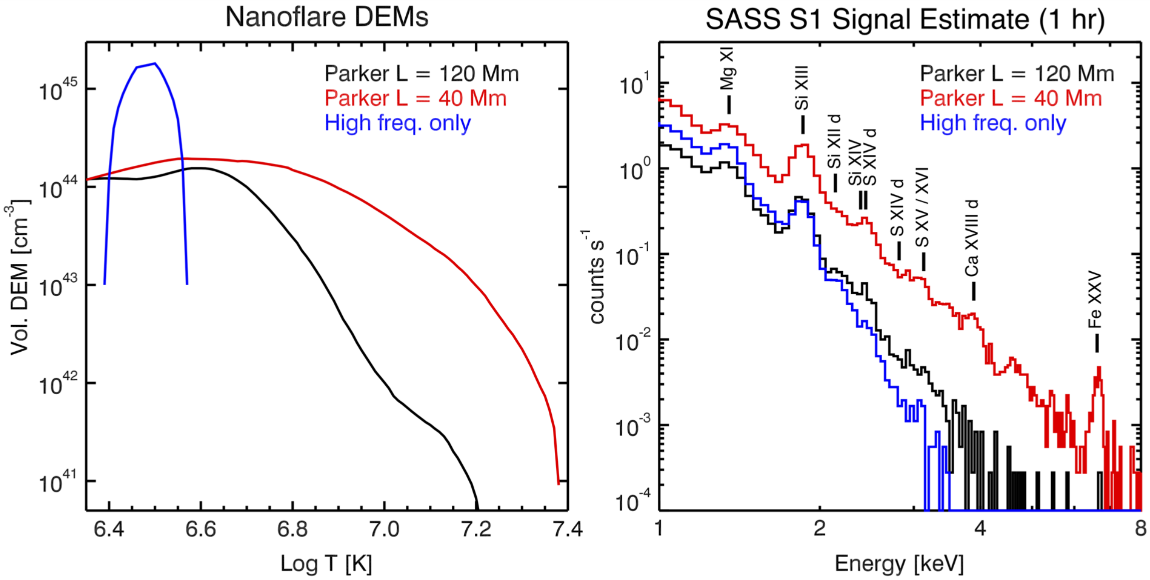
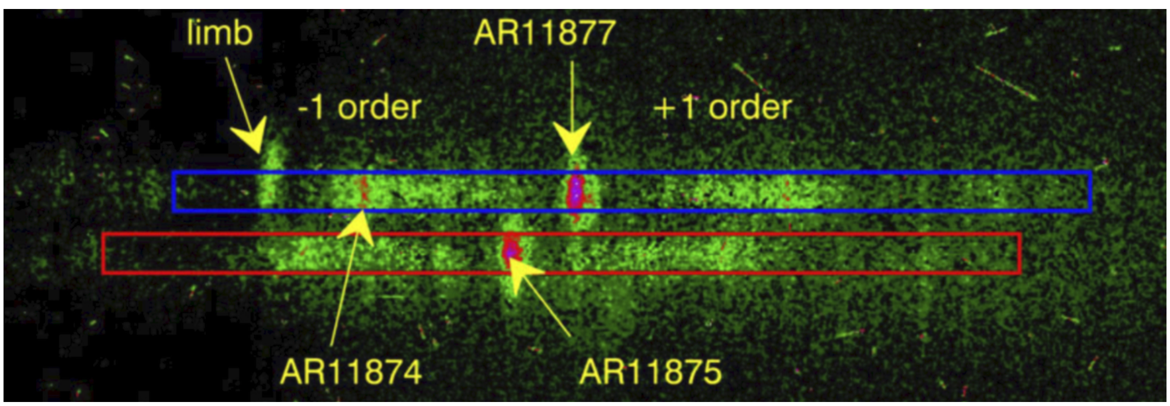


Fig. 5. SXR spectra (right) are highly sensitive to even small amounts of hot plasma and thus provide strong constraints on nanoflare coronal heating models (left), where low-frequency ("Parker") models predict high (~10 MK) temperatures while high-frequency models do not. [CLICK TO ENLARGE]



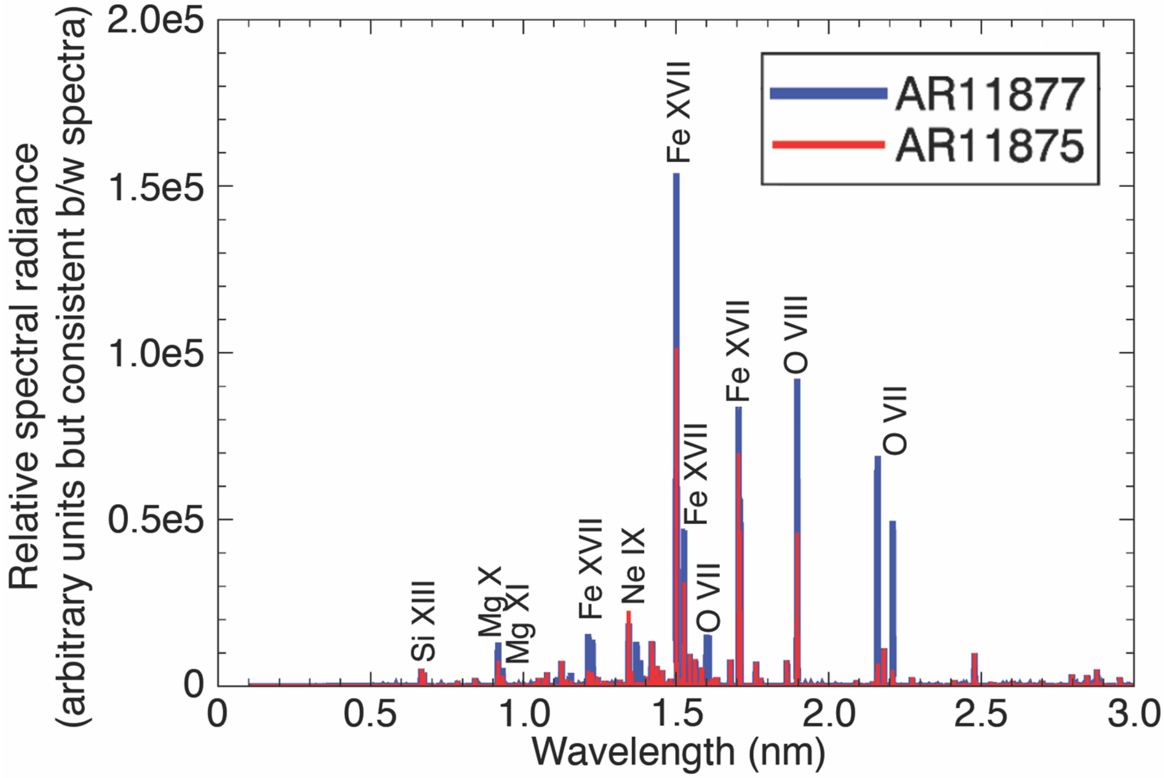


Fig. 6. CubIXSS will compile numerous spectro-spatial images of individual ARs to enable development and validation of new algorithms to analyze such rich data. MOXSI prototype observations of multiple ARs from a 2013 sounding rocket [top] provide proof of concept for deriving the spectra of individual ARs [bottom] and highlight the need for new algorithms validated against robust data sets. CubIXSS data quality will be far superior (see Fig. 7 in Instruments & Expected Data panel). (Adapted from Wieman et al. 2015.) [CLICK TO ENLARGE]

INSTRUMENTS & EXPECTED DATA

CubIXSS employs a suite of X-ray instruments, including a novel diffractive slitless spectrograph (called MOXSI) and spatially integrated spectrometers (called SASS), for solar spectroscopy from 0.22 keV up to 50 keV across a wide dynamic range of flux.

Multi-Order X-ray Spectral Imager (MOXSI)

MOXSI provides both spectrally dispersed and broadband multi-filter SXR images simultaneously, to observe solar flares and individual active regions.

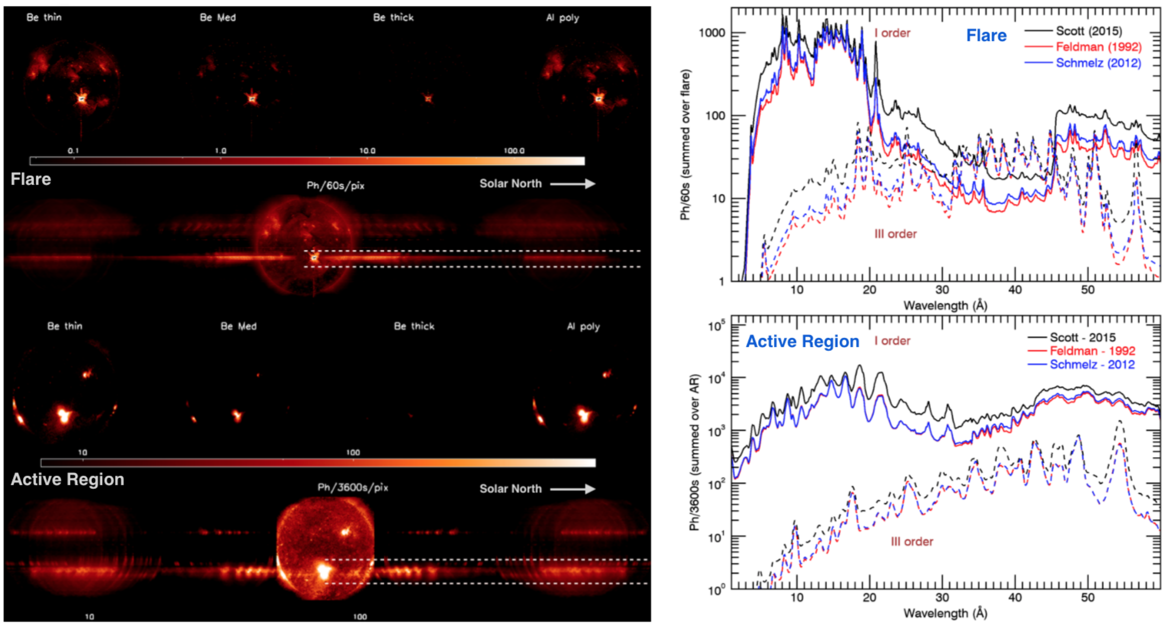


Fig. 7. Simulated MOXSI observation of an X1 flare (top) and quiescent AR (bottom). SDO/AIA and Hinode/XRT data are used to generate a thermal model at each pixel, matched to MOXSI spatial resolution and folded through filtergram & grating responses. (The blooming and speckling is an artifact of the AIA/XRT processing; MOXSI does not suffer from this.) Images are scaled as sqrt and slightly saturated to aid interpretation; simulations are condensed, actual MOXSI solar images have wider separation. +1st and +3rd order intensity summed over the feature (between white lines) clearly distinguish different abundance models even before spectral inversion and forward-modeling. [CLICK TO ENLARGE]

Spectral range: 1–55 Å (0.22–12 keV)

Spectral resolution (FWHM): 0.24–0.34 Å (0.055 Å/pixel)

Spatial resolution (FWHM): 25″–34″ (5.7″/pixel)

Cadence: High: 20 s; Low: 5 min

MOXSI contains a miniaturized slitless imaging spectrograph to provide spectro-spatial measurements, wherein SXR spectra of individual features are dispersed by a transmission grating. The intense solar SXR flux enables direct imaging up to 10 keV using just a pinhole aperture and short focal distances. On-board motion compensation and per-pixel thresholding algorithms minimize jitter-induced blurring and maximize signal-to-noise for optimal imaging even over long effective integration periods.

MOXSI also includes 4 additional pinhole apertures with different thin filters, offset from the primary aperture. These pinholes provide SXR filtergrams similar to those from Hinode X-ray Telescope (XRT), providing non-dispersed images with coarse spectral information as validation for spectro-spatial analysis algorithms.

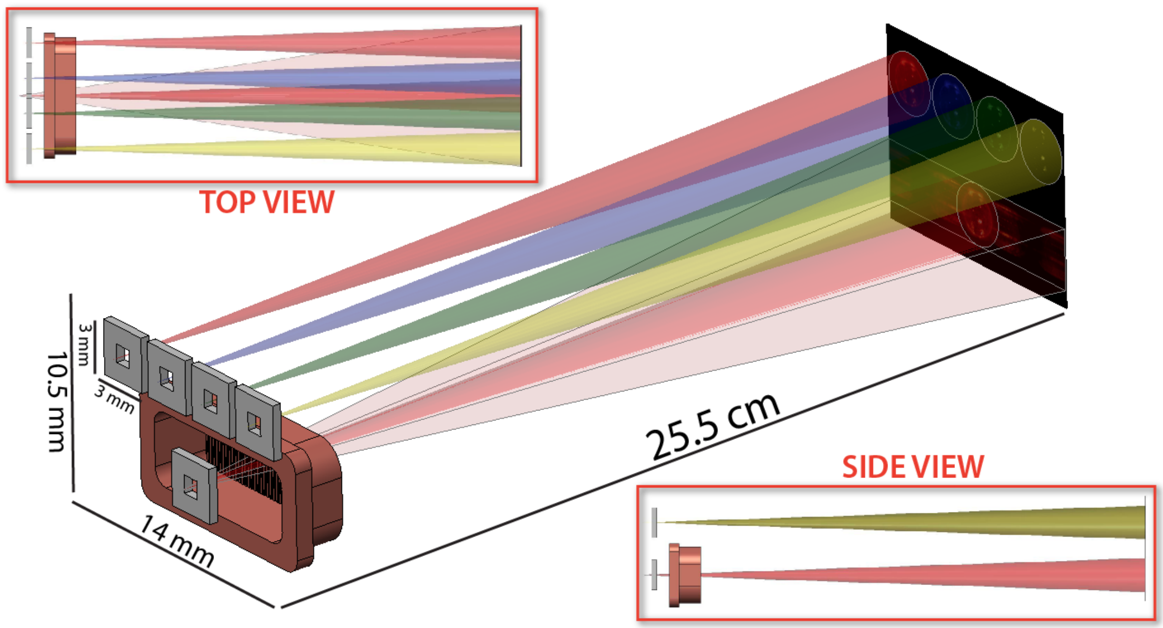


Fig. 8. MOXSI optical schematic. Four pinhole apertures provide filtergram images on the top half of the detector. Light from the bottom pinhole passes through the transmission grating to yield a spectrally dispersed image on the bottom half. (See also Fig. 7, above.) [CLICK TO ENLARGE]

A prototype MOXSI instrument, based on a modified SDO/EVE(SAM) design with EVE(ESP) grating, demonstrated proof of concept on a NASA sounding rocket in 2013 (see Fig. 6 in Scientific Objectives panel, and Wieman et al. 2016 (https://doi.org/10.1007/s11207-016-0999-6)).

Small Assembly for Solar Spectroscopy (SASS)

SASS provides high-sensitivity SXR spectra integrated over the entire solar disk, with extended spectral coverage and dynamic range.

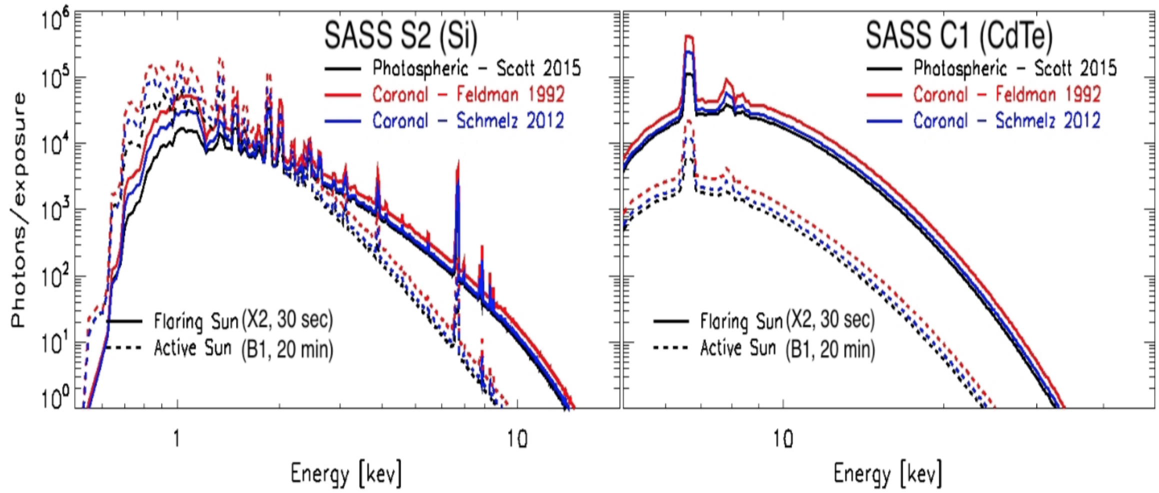


Fig. 9. SASS generates strong, well-resolved spectra with required SNR for all required activity levels and cadences, and directly distinguishes between different abundance models. (Shown: channels S2, left; C1, right; channels S1 & S3 omitted for brevity.) See also Fig. 4 in Science Objectives panel. [CLICK TO ENLARGE]

Spectral range: 0.5–20 keV (Si) and 5–50 keV (CdTe)

Spectral resolution (FWHM): 0.06–0.2 keV (Si) and 0.3–0.5 keV (CdTe)

Spatial resolution (FWHM): N/A

Cadence: High: 1 s; Low: 1 min

Table 1. SASS channel parameters provide overlapping sensitivity. [CLICK TO ENLARGE]

Channel	Aperture ∅ (mm)	Filter (µm)	Optimal Flux Range
S1 (Si)	1.0	15 Be	Min – ≳B5
S2 (Si)	0.22	20 Be	~B1 – ≳M5
S3 (Si)	0.16	50 Be	~C1 – ≳X5
C1 (CdTe)	5.64	108 Al	~C1 – ≳X1

SASS comprises four COTS Amptek X123 X-ray spectrometers with tailored apertures and filters to achieve sensitivity over a wide dynamic range. A silicon drift detector (SDD) with 0.5 mm thickness provides the required SXR line and continuum sensitivity from 0.5 to 20 keV; a cadmium telluride (CdTe) detector with 1 mm thickness provides increased sensitivity for Fe XXV and continuum emission from 5 to 50 keV during flares. Prototype SASS-Si X123s have successfully flown on three NASA sounding rockets (Caspi et al. 2015b (https://doi.org/10.1088/2041-8205/802/1/L2); Schwab et al. 2020 (https://doi.org/10.3847/1538-4357/abba2a)) and on MinXSS-1 (Woods et al. 2017 (https://doi.org/10.3847/1538-4357/835/2/122); Moore et al. 2018 (https://doi.org/10.1007/s11207-018-1243-3)). A prototype SASS-CdTe was flight-qualified on the GRIPS balloon (Caspi et al. 2016 (https://www.researchgate.net/publication/303875839_First_flight_of_SMASH_the_SwRI_Miniature_Assembly_for_Solar_Hard_X-rays)).

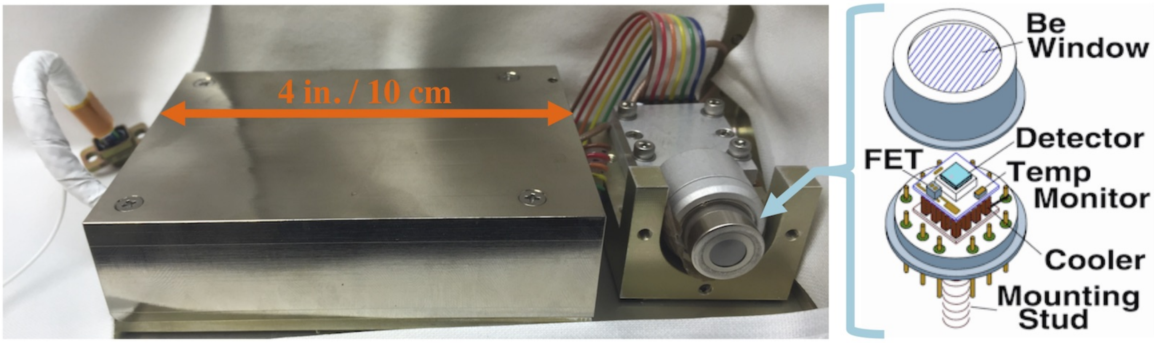


Fig. 10. The X123 detector head is a sealed vacuum vessel including thermo-electric cooler (TEC) & beryllium window, with integrated preamp. The compact electronics include a complete multi-channel spectral analyzer and high- and low-voltage power supplies. The X123-FastSDD and -CdTe are identical in form, fit, and interface. [CLICK TO ENLARGE]

MISSION DETAILS

CubIXSS combines MOXSI and SASS in a compact, inexpensive, high-TRL 6U CubeSat spacecraft.

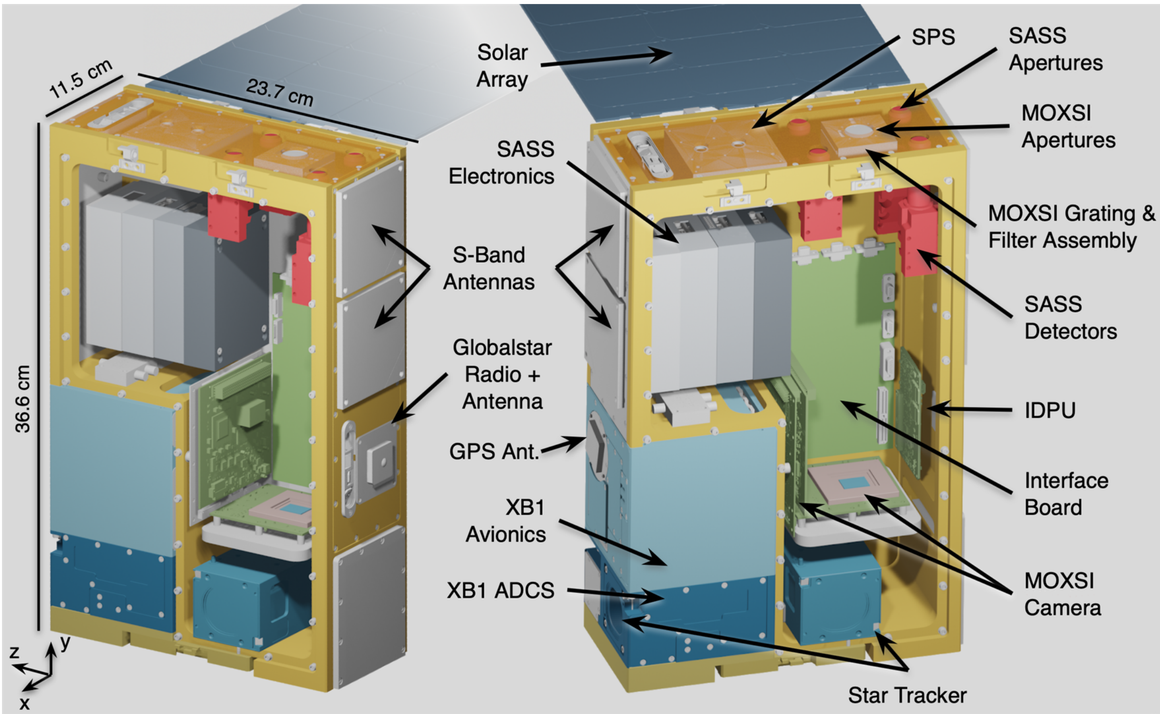


Fig. 11. CubIXSS 6U spacecraft layout. Solar panels & instruments are Sun-pointed. Second solar array, top structural panel, and MOXSI metering structure are suppressed. [CLICK TO ENLARGE]

The spacecraft bus, including structure and avionics, is high-heritage from Blue Canyon Technologies and provides high-precision Sun-pointing attitude control and high-speed S-band communication. A Solar Position Sensor (SPS) from LASP provides 1-arcsec pointing knowledge. The Instrument Data Processing Unit (IDPU) includes high-heritage, high-performance CPU, FPGA, and flash RAM to process and store SASS, MOXSI, and SPS data.

CubIXSS is designed to accommodate a wide range of orbital parameters. A sun-synchronous polar dawn/dusk orbit (6am LTDN) is preferred but the reference design is for a "worst case" mid-inclination eclipsing orbit. Solar panels and batteries are sized to ensure power-positive operation in all sunlit cases with <20% depth of discharge during eclipse.

Table 2. CubIXSS notional mission elements [CLICK TO ENLARGE]

Mission Element	**Reference Design**
Orbit	470 km × 600 km @ 66°
Eclipse Period	34.9 min (max)
Mission Lifetime	12 months
Spacecraft	6U CubeSat, 3-axis stabilized, Sun pointed
Mass	9.25 kg (CBE)
Power	24.3 W (orbit-avg.) (CBE)
ADCS	Control: 7″ (1σ) (XB1) Stability: 1″/sec (1σ) (XB1) Knowledge: 1″ (3σ) (SPS)
Ground System	ATLAS (S-band 3.5m)
Downlink Time	42 min/day
Data Capture	472 MB/day

STATUS AND OUTLOOK

CubIXSS has been funded for a formulation phase through the ROSES 2019 Heliophysics Flight Opportunities for Research and Technology (H-FORT) opportunity, with a Concept Study Report submitted in mid-December 2020. If selected, the project would begin in early 2021, with an anticipated launch in late 2023 followed by a 1-month commissioning. The baseline mission is for one year of science operations, but the CubIXSS design is robust and we hope to continue extended operations for additional years beyond baseline.

Nov 2019 -- Proposal submitted to H-FORT

Jul 2020 -- Selected for formulation

Dec 2020 -- Concept Study Report submitted

Feb 2021 -- Program start

Jul 2023 -- Launch ready

Oct 2023 -- Notional launch for 1-year mission

CubIXSS data will be open to the community and published in various levels, including "raw" and processed. Open-source processing tools, including those used to generate higher-level data, and calibration parameters will also be made available.

Table 3. CubIXSS data levels and expected availability [CLICK TO ENLARGE]

Level	MOXSI	SASS	Available
0	Decommutated images with metadata from spacecraft and sensor housekeeping required for calibration	Decommutated spectral data in separate files for each channel including metadata and Sun sensor information	Launch + 1 mo.
1	Linearized data in counts per second with full metadata including World Coordinate System pointing and projection information	As above in units of count rate normalized by live time, gain corrected so spectra are reported on a uniform scale, including full metadata	Launch + 2 mo.
2	(1) Differential emission measure maps and (2) extracted spectra at high cadence for selected flares and active regions	Spectra in physical (photon) units, merged into single high-dynamic-range spectral composite products	Launch + 3 mo.

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Google Scholar (https://scholar.google.com/citations?user=6GkkNKEAAAAJ&hl=en)

ResearchGate (https://researchgate.net/profile/Amir_Caspi)

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IMDb (https://www.imdb.com/name/nm9256938/)

ABSTRACT

The *CubeSat Imaging X-ray Solar Spectrometer* (*CubIXSS*) is a 6U CubeSat currently in a formulation phase under the 2019 NASA H-FORT program. *CubIXSS* is motivated by a compelling overarching science question: what are the origins of hot plasma in solar flares and active regions? Elemental abundances are a unique diagnostic of how mass and energy flow into and within the corona, and *CubIXSS* addresses its science question through sensitive, precise measurements of abundances of key trace ion species, whose spectral signatures reveal the chromospheric or coronal origins of heated plasma across the entire range of coronal temperatures, from ~1 to >30 MK. *CubIXSS* measurements of the coronal temperature distribution and elemental abundances directly address longstanding inconsistencies from prior studies using instruments with limited, differing temperature and composition sensitivities.

CubIXSS comprises two co-optimized and cross-calibrated instruments that fill a critical observational gap:

- MOXSI, a novel diffractive spectral imager using a pinhole camera and X-ray transmission diffraction grating to achieve spectroscopy of flares and active regions from 1 to 55 Å, with spectral resolution of 0.24 Å FWHM and a spatial resolution of 25 arcsec FWHM; and
- SASS, a suite of four spatially-integrated off-the-shelf spectrometers for high-cadence, high-sensitivity measurements of soft and hard X-rays, from 0.5 to 50 keV, with spectral resolution from 0.06 to 0.5 keV FWHM.

If selected for implementation, *CubIXSS* will launch in late 2023 to observe intense solar flares and active regions during the rising phase of the solar cycle. Its nominal 1-year mission is well timed with perihelia of *Parker Solar Probe* and *Solar Orbiter*, and with the launches of complementary missions such as the *PUNCH* Small Explorer. *CubIXSS* is also a pathfinder for the next generation of Explorer-class missions with improved capabilities for SXR imaging spectroscopy. We present the *CubIXSS* motivating science background, its suite of instruments and expected performances, and other highlights from the completed Concept Study Report, including novel analysis techniques to fully exploit the rich data set of *CubIXSS* spectral observations.